

# Metabolic Costs and Biomechanics of Level Ambulation in a Planetary Suit

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## PREFACE

NASA's Apollo program was a remarkable human achievement, however, fewer than 20 total program EVAs were performed with no crew member performing more than three. With NASA planning to return to the Moon to conduct thousands of EVAs, we believe that EVA systems need to be optimized for human performance and that designs used during the Apollo program had too many limitations to serve as the base designs for the Constellation Program. Our vision is to provide the information for EVA systems to be developed resulting in low overhead and as close to or better performance than seen shirt-sleeve on Earth. In this report, we not only highlight some of the factors that affect human performance during suited operations, but also describe testing methods, facilities, equipment, personnel and future products that so that we can continue to build on the results of this test.

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# 1 INTRODUCTION

Current understanding of suited human performance in reduced-gravity environments includes observations from Apollo lunar surface EVAs and from a limited group of studies conducted in partial gravity simulation environments (1) (2). The Constellation Program (CxP) EVA Systems Project Office (ESPO) working with the EVA Physiology, Systems, and Performance Project (EPSP), and Anthropometry and Biomechanics Facility (ABF), is developing design requirements for the next generation lunar EVA suit and has initiated a series of tests to understand human performance and suit kinematics under a variety of simulated lunar EVA conditions. These studies, conducted in multiple partial-gravity environments include matched unsuited controls, so that the specific metabolic costs and biomechanics of the suit can be understood. The eventual results of these studies will provide evidence-based recommendations for suit weight, mass, center of gravity (CG), pressure, and suit kinematic constraints that optimize human performance in partial-gravity environments.

The first of these studies, the EVA Walkback Test (EWT) was conducted using the Partial Gravity Simulator (POGO) in the Space Vehicle Mock-Up Facility (SVMF, Building 9) and the Mark III (MKIII) spacesuit. The MKIII was used as it represents a suit concept that provides dynamic ranges of motion considered necessary for a wide variety of planetary tasks. Results from the EWT showed initial estimates for the total metabolic cost of suited locomotion in the reduced gravity environments of the Moon (1/6-g) and Mars (3/8-g) as well as preliminary biomechanical parameters (1). For this study, Integrated Suit Test 1 (IST-1), suited conditions had a constant CG location and suit mass, while suit offload (weight), pressure, and suit kinematic constraints (waist locked versus unlocked) were varied to determine their individual effects on lunar ambulation. For unsuited conditions, either the subject's mass was constant while the offload was varied or the subject's weight was held constant while the subject's mass was varied.

This final report presents the key findings of IST-1 as it relates to suited and unsuited human performance of treadmill locomotion on the POGO. Additional tests have been completed or are being planned to better understand human performance during exploration tasks and while wearing different suits as well as the limitations of testing in different lunar analog environments. The series of tests comprising IST-1 was conducted from March 6, 2007 through July 24, 2007.

## 1.1 Test Objectives

The purpose of IST-1 was to expand on the initial findings from the energy-velocity tests of the EWT. Specifically, the primary objectives of this test follow:

1. To identify the individual contributions of weight, mass, pressure, and suit kinematics to the overall metabolic cost of the MKIII suit in its POGO configuration (121 kg [265 lb] including mass of portable life support system (PLSS) mockup and gimbal, 29.6 kPa [4.3 psi]) during lunar ambulation.
2. To quantify the effects of the following factors on suited and/or unsuited metabolic rate, biomechanics, and subjective ratings during level ground ambulation at varied speeds:
  - a. Suited – varied suit pressure at constant offload, mass and CG
  - b. Suited – varied suit offload (weight) at constant pressure, mass and CG

- c. Unsuited – varied offload (weight) at constant mass and CG
- d. Unsuited - varied mass at constant offload and CG
- 3. To compare the MKIII at POGO configuration to the MKIII at POGO configuration with the waist bearing locked.
- 4. To develop predictive models of metabolic rate, subjective ratings, and suit kinematics based on measurable suit, task, and subject parameters.

Beyond the primary objectives, additional scientific and engineering objectives and/or applications of IST-1 data were as follows:

- 1. To define standard measures and protocols for objectively evaluating future exploration suit candidates and requirements verification of the flight suit.
- 2. To understand specific human performance limitations of the suit compared to matched shirt-sleeve controls.
- 3. To collect metabolic and ground-reaction force data to develop an EVA simulator for use on future prebreathe protocol verification tests
- 4. To provide data to estimate consumables usage for input to suit and PLSS design.
- 5. To assess the cardiovascular and resistance exercise associated with partial-gravity EVA for planning appropriate exploration exercise countermeasures.

## 2 METHODS

### 2.1 Subjects

Subjects were recruited from a pool of personnel who typically perform EVA-suited studies for the JSC Engineering Directorate and from the group of astronauts selected to support exploration EVA studies. Suit fit checks in the MKIII suit were performed on a range of subjects and only those who had good suit fit were considered for inclusion in this study because of potential medical safety issues. From this list, 6 male astronaut subjects (Table 1) participated in the data collection phases of the study. One additional subject performed the  $VO_2pk$  test, but did not complete the data collection sessions because of poor suit fit. At the time of testing, no available female astronauts properly fit in the MKIII suit.

**Table 1. Subject characteristics**

n = 6	Height (cm)	Body Mass (kg)	Age (years)	$VO_2pk$ (ml/min/kg)	Leg Length (cm)
<b>Average</b>	179.1	80.7	44.8	50.8	104.0
<b>St. Dev.</b>	4.8	8.5	6.9	6.7	3.8
<b>Max</b>	185.9	86.4	52.0	60.7	109.2
<b>Min</b>	174.6	68.2	37.0	42.6	100.2

All subjects successfully passed a modified Air Force Class III physical or equivalent examination. Each subject was provided verbal and written explanations of the testing protocols and the potential risks and hazards involved in the testing and signed the JSC Human Research documentation indicating their understanding and consent. All testing protocols were reviewed and approved by JSC's Committee for the Protection of Human Subjects and appropriate test readiness reviews were conducted before testing.



## 2.2 Test Hardware

### 2.2.1 Partial-Gravity Simulator (POGO)

All IST-1 data collection sessions were performed using the SVMF's POGO system to provide simulated partial-gravity conditions. The POGO system and gimbal support structure were unchanged from those used during the EVA Walkback Test (1).

### 2.2.2 Mark III Advanced Space Suit Technology Demonstrator EVA Suit

For suited testing, the MKIII suit (Figure 1) was used as it represents a suit concept that provides dynamic ranges of motion considered necessary for a wide variety of planetary EVA tasks within today's technology level given other constraints that must be considered in pressure garment design. The MKIII also had an existing interface for integration with the POGO and allowed for varied pressure testing. Thus, the MKIII provided a valid test bed from which attainable requirements for future suit development can be derived. The MKIII is a hybrid space-suit configuration composed of hard elements, such as a hard upper torso and brief section, and of soft components such as fabric elbows and knees that are designed to handle operating pressures of up to 55.0 kPa (8.0 psi). Another feature of the suit is the use of convolutes and bearings allowing multi-axial mobility joint systems. The shoulder is a rolling convolute with scye and upper arm bearing. At the waist, both a bearing and rolling convolute are used to allow flexion, extension, and rotation. Multiple bearing and convolutes at the hip and thigh allow abduction, adduction, flexion, and extension. The suit is entered through a hatch on the backside of the hard upper torso (rear entry suit) that also accommodates integration of a backpack PLSS. Subjects are stabilized in the suit by shoulder straps. The boots are modified commercial work boots with flexible soles for walking and a convoluted ankle joint for mobility. The MKIII has modular leg, arm, and boot soft-goods components that allow individualized adjustments with metal sizing rings. Foam padding is used to improve fit and to avoid pressure or rubbing spots.

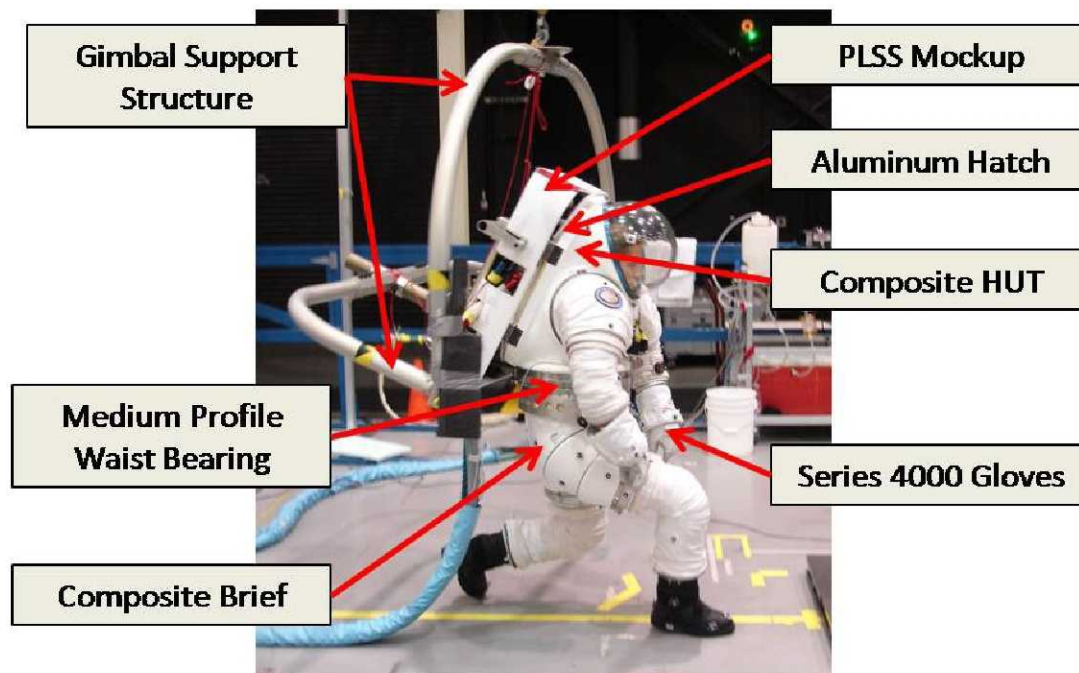


Figure 1. Mark III Advanced Space Suit Technology Demonstrator

Different hard components materials can be used depending on test objectives. The MKIII, as tested in IST-1, used the following components: volumetric backpack PLSS mockup (19 kg), aluminum hatch, composite hard upper torso, composite brief and medium profile waist bearing. The gloves used during ambulation trials were the series 4000's because they were rated to higher pressures.

During testing sessions certified breathing air was provided by a compressed air tube trailer at a standard flow rate of 4.2 L/s (9.0 cubic feet per minute) through a manifold and transfer hoses and reduced to the appropriate pressure between 6.9 and 44.8 kPa (1.0 and 6.5 psi). Internal suit cooling was provided via a closed water loop that circulates through an ice/water chiller to cool the test subject's class III modified shuttle liquid-cooling garment (LCG). The system was powered by an external pump (~109 kg/hr) and could deliver a minimum suit inlet temperature of 4 °C or a maximum of 28 °C when the chiller bypass valve was activated. Communication with the suited test subject was available via a system comprised of hardwire head sets.

For the purposes of this report, "suit" refers to the pressure garment, PLSS mockup, and gimbal support structure.

### 2.2.3 Shirt-Sleeve Harness

Two separate harnesses were combined to allow for maximum range of motion and subject comfort. Figure 2 shows pictures of the harness components. The torso vest harness (Amspec # JV0100P) (also known as a "jerk vest" in Hollywood) was combined with a Dakine Fusion kite surfing harness. The leg straps of the jerk vest were not used. Additional pickup points were sewed to the kite-surfing harness allowing both harnesses to be connected via 1 inch nylon webbing and buckles. Subjects were connected to the POGO spreader bar with 4 attachment points on the lower portion of the jerk vest.



Figure 2. Shirt-sleeve harness components: Amspec jerk vest and Dakine Fusion harness



#### 2.2.4 X-Vest

The X-Vest (Xtreme Worldwide Athletic Equipment, Houston, TX) is a commercially available vest allowing the addition of up to 84 lb of mass in 1-lb increments (Figure 3). The vest is designed to be a training tool for athletes, military, firefighters and law enforcement and allows the addition of significant mass, while fitting tightly via elastic straps around the torso. There are 8 rows where weights could be added. In all cases, weights were added in equal proportion front and back with the weights going into the vest in the following order: 1) lower inside pockets, 2) upper inside pockets, 3) lower outside pockets, and 4) upper outside pockets. During trials, the vest was worn as the outermost garment on top of the subject's clothing and the shirt-sleeve harness.



Figure 3. X-Vest

#### 2.2.5 VacuMed Oversized Treadmill

The treadmill used for testing in the SVMF was a customized VacuMed model #13610 large research treadmill owned by the EVA & Spacesuit Systems Branch (Figure 4). With a walking surface 1.5 meters wide and 2.4 meters in length, it allows speeds from 0.2 to 12 m•s<sup>-1</sup> (0.5 to 27.0 mph) with speed resolutions of 0.44 m•s<sup>-1</sup> (0.1 mph) and grades from 10 percent decline to 30 percent incline. The treadmill was instrumented with 4 force plates (AMTI Model #OR6-5-2000) placed under the deck and belt of the treadmill. These were provided and integrated by the ABF. Placement of the 4 force plates allowed only normal forces to be calculated.



Figure 4. VacuMed research treadmill

## 2.3 Testing Protocols

### 2.3.1 Peak Oxygen Consumption ( $\text{VO}_{2\text{pk}}$ ) Test

To compare energy expenditure across the different conditions planned for this test, subjects performed a graded treadmill exercise test to determine their aerobic capacity via measurement of peak oxygen consumption, or  $\text{VO}_{2\text{pk}}$ . The test began with a 5 min warm-up at  $1.56 \text{ m}\cdot\text{s}^{-1}$  followed by three stages lasting 3 min each on a level surface, starting at  $2.68 \text{ m}\cdot\text{s}^{-1}$  and increasing  $0.45 \text{ m}\cdot\text{s}^{-1}$  at the start of each new stage. After the third stage, the speed remained the same and the incline on the treadmill surface was increased 3 percent at the start of each subsequent minute (3) (4). The subject continued exercising through these stages as long as possible, to maximal effort.  $\text{VO}_{2\text{pk}}$  and peak heart rate were determined by the highest 1-min average attained during the test. From the  $\text{VO}_{2\text{pk}}$ , measured levels of energy expenditure during subsequent test sessions can be evaluated as percentages of  $\text{VO}_{2\text{pk}}$  to ensure subject safety and allow valid relative comparisons among subjects. This phase of IST-1 was performed from March 6, 2007 to May 18, 2007.

### 2.3.2 Establishment of Individualized Preferred Transition Speed (PTS)

To establish accurate baseline metabolic and biomechanical data for a range of walking and running speeds, it was first necessary to determine the preferred transition speed (PTS) from walking to running. Therefore, before their unsuited energy velocity test, each subject's unsuited PTS was determined at 1/6-g using identical methods to those described in the EVA Walkback Report (1). Once the PTS was determined for each gravity level, 3 walking and 3 running velocities were assigned (Table 2) such that the PTS and immediate range above and below it would be avoided during data collection. Three speeds were selected for data collection to allow investigators to understand the shape of the metabolic curve in both the walking and running ranges.

**Table 2. Speeds used for data collection**

Stage	Speed	Comments
1	PTS minus $0.67 \text{ m}\cdot\text{s}^{-1}$ (1.5 mph)	Subtract $0.22 \text{ m}\cdot\text{s}^{-1}$ per stage; need smaller increments for walking
2	PTS minus $0.45 \text{ m}\cdot\text{s}^{-1}$ (1.0 mph)	
3	PTS minus $0.22 \text{ m}\cdot\text{s}^{-1}$ (0.5 mph)	Subtract $0.22 \text{ m}\cdot\text{s}^{-1}$ to assure walking out of transition zone
<b>Preferred Transition Speed</b>		<b>No data collected in transition zone</b>
4	PTS plus $0.22 \text{ m}\cdot\text{s}^{-1}$ (0.5 mph)	Add $0.22 \text{ m}\cdot\text{s}^{-1}$ to assure running out of transition zone
5	PTS plus $0.67 \text{ m}\cdot\text{s}^{-1}$ (1.5 mph)	Add $0.45 \text{ m}\cdot\text{s}^{-1}$ to distinguish metabolic and biomechanical differences at running speeds
6	PTS plus $1.12 \text{ m}\cdot\text{s}^{-1}$ (2.5 mph)	

### 2.3.3 POGO Offloading

Before the beginning of any trial, the target weight for the subject was verified with the integrated force plates in the treadmill. For suited tests, the target weight was adjusted to  $\pm 0.5 \text{ kg}$  (1 lb). During unsuited testing, the target weight was adjusted to  $\pm 1.4 \text{ kg}$  (3 lb) as this allowed for much quicker adjustments and minimized the overall time that a subject was suspended in the harness by the POGO.

#### 2.3.4 Varied Mass Test (Unsuited)

Each subject translated on a level treadmill (0 percent grade) for 3 min at each of the six individually prescribed velocities based on PTS, while the POGO system provided partial weight relief. Subjects were offloaded to the weight that matched their weight during the suited trial with a suit system mass of 121 kg at lunar gravity (Figure 5). Subjects completed the six speed trial four times with each trial set at a different mass but constant weight. Speed order was always from slowest to fastest for every condition tested. Masses of 0, 11.4, 22.7, and 34 kg (0, 25, 50, and 75 lb) were evenly distributed with respect to each subject's CG using the X-vest, while each subject's overall weight was kept constant by increasing the POGO offloading force to offset the added mass in each condition. Varied mass trial order was balanced. Varied mass test conditions were performed between May 8, 2007 and July 24, 2007.



**Figure 5. Instrumented unsuited subject performs treadmill locomotion while partially offloaded from POGO overhead**

#### 2.3.5 Varied Pressure Test (Suited)

Each subject donned the MKIII suit with initial pressure of 29.6 kPa (4.3 psi) and in-suit oxygen concentration of 21 percent provided via certified breathing air as are customary during EVA test operations with the MKIII suit. Each subject translated on a level treadmill (0 percent grade) for 3 min at each of the six prescribed velocities while the POGO system provided partial weight relief to



simulate lunar gravity (Figure 6). Subjects completed the ambulation trials at each of 5 different suit pressures: 6.9, 20.7, 29.6, 34.5, and 44.8 kPa (1.0, 3.0, 4.3, 5.0, and 6.5 psi). Varied pressure trial order was balanced. Suit mass was constant at 121 kg in these trials. Varied pressure test conditions were performed between March 22, 2007 and May 25, 2007.



**Figure 6. Suited subject performs treadmill locomotion while partially suspended from POGO overhead**

#### 2.3.6 Varied Weight Test (Unsuited and Suited)

Ambulation at the same 6 speeds used in the varied pressure and varied mass conditions was repeated in both suited and unsuited conditions at a range of simulated suit weights while holding mass (121 kg) and suit pressure (29.6 kPa [4.3 psi]) constant. For suited testing, POGO offloading force was adjusted to different gravity levels of 0.12-g, 0.17-g, 0.22-g, 0.27-g, and 0.32-g. For these trials, the mean total gravity adjusted weight (TGAW) defined as the suit, gimbal and subject mass (assume 80 kg subject) multiplied by the gravity level was 236, 334, 431, 529 and 627 Newtons (N) (53, 75, 97, 119, and 141 lb). If these were the actual TGAW on the Moon, it would require a suit mass of approximately 63, 121, 186, 247, and 308 kg. Unsuited testing was performed at the weight matched conditions of 0.17-g, 0.27-g, and 0.32-g. Varied weight test conditions were performed from April 4, 2007 to July 24, 2007.

By using a constant mass suit, there was no change to the inertial properties or to mass distribution. Because suits of varied mass were not available and current POGO hardware does not provide the capability to lift significant added mass, the closest comparison we could make to understanding how a change in suit mass affects human performance was to simulate a change in mass by varying the offload level to see how a constant mass suit affected human performance at different TGAW, otherwise known as weight on the ground. A combination of unsuited varied mass testing in this study as well as future suited and/or unsuited testing will be required to understand how mass properties of the suit affect performance.

## 2.4 Metabolic Data Collection and Analysis

During the  $\text{VO}_{2\text{pk}}$  and unsuited tests, metabolic rate was determined from the continuous measurement of  $\text{VO}_2$ , carbon dioxide ( $\text{CO}_2$ ) production, and expiratory volume ( $V_E$ ) using a headset/mouthpiece connected to a True One 2400 metabolic cart (Parvo Medics, Provo, UT). Heart rate during the  $\text{VO}_{2\text{pk}}$  test was monitored from 12-lead electrocardiogram (ECG) recordings, and during submaximal tests from a heart rate monitor (Polar 810i, Lake Success, NY).

During exercise in the MKIII suit, metabolic rate was based on measured suit ventilation rate, expired  $\text{CO}_2$  concentration in the exhaust umbilical (CD-3A Infrared Carbon Dioxide Analyzer, AEI Technologies, Pittsburgh, PA) and the regression between  $\text{VCO}_2$  and  $\text{VO}_2$  as measured during the  $\text{VO}_2$  peak test. This technique and hardware were identical to those currently used during suited Neutral Buoyancy Lab (NBL) tests.

The metabolic rates represent the highest 1-min average during each of the 3-min walking or running stages. Metabolic rate was defined as mL of  $\text{O}_2$  consumed per kg of the subject's body mass, per minute ( $\text{mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ ). Transport cost was defined as mL of  $\text{O}_2$  consumed per kg of the subject's body mass per km traveled ( $\text{mL}\cdot\text{kg}^{-1}\cdot\text{km}^{-1}$ ). Second order polynomial regression trend lines were used to fit metabolic rate versus the dependant variables.

### 2.4.1 Calculating Contributions of Weight, Inertial Mass, Pressure and Suit Kinematics to Overall Metabolic Cost of MKIII Suit

Individual contributions to the total metabolic cost of the suit were based on a second order polynomial regression model combining data from IST-1 and the unsuited baseline data from the EWT (1). The unsuited baseline metabolic rate and suited metabolic rate were calculated by using the regression equation relating speed to metabolic rate. The total metabolic cost of the suit was determined by subtracting the unsuited trials from the suited trials. Two different models exist because of different methods of calculating the cost of weight. In the unsuited-weight cost model, the metabolic cost of weight was determined by calculating the difference between unsuited and unsuited weight-matched trials. In the suited-weight cost model, the cost of weight was determined by extrapolating regression equations back to a 0.0 N suit weight and calculating the difference between 0.0 N and 1187 N (121 kg). Models discussed in this report used the unsuited-weight cost model. The cost of suit pressure was determined by extrapolating regression equations back to 0.0 kPa and determining the difference between 0.0 and 29.6 kPa (4.3 psi). The other component is a large mix of factors primarily comprised of suit factors such as mass, kinematic constraints, and stability as well as system level components such as harnessing differences between unsuited and suited conditions. There also may be other factors that are unknown and thus not accounted for. This

“other factors” category was calculated by subtracting the metabolic cost of pressure and weight from the total metabolic cost of the suit.

#### 2.4.2 Significant Metabolic Differences

In comparing the metabolic costs of different suited conditions, it is important to define some level of metabolic rate that is deemed significant. Because of the limited sample size ( $n = 6$ ), inferential statistics were not used, therefore statistical significance was not calculated. For these analyses a change in metabolic rate of  $3.5 \text{ mL} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$  was chosen for practical significance. This is equivalent to resting metabolic rate and 10 percent of the  $\text{VO}_{2\text{pk}}$  in a subject with a  $\text{VO}_{2\text{pk}}$  of  $35 \text{ mL} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$  who would be representative of a slightly deconditioned crewmember. The average ISS crewmember has a preflight  $\text{VO}_{2\text{pk}}$  of  $43.7 \pm 6.1 \text{ mL} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$  (JSC’s Exercise Physiology Lab Database).

Our assumption is that a  $3.5 \text{ mL} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$  change in is not perceptible by most subjects. This was further supported by data collected during this study, where variation in  $\text{VO}_2$  greater than  $3.5 \text{ mL} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$  was often seen within a given level of exertion defined by ratings of perceived exertion (RPE). Within a given RPE for an individual subject, variation was often greater than  $3.5 \text{ mL} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$  and could be as much as 2 to 3 times that value depending on the subject. Figure 7 demonstrates this variability of  $\text{VO}_2$  within a given RPE for three different subjects with each horizontal gridline representing the significant level of  $3.5 \text{ mL} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$ . Also, based on linear regression of RPE and  $\text{VO}_2$  from  $\text{VO}_{2\text{pk}}$  testing results for this study and the EWT ( $n = 8$ ), an increase in RPE occurred with an increase in  $\text{VO}_2$  of  $4.2 \pm 0.5 \text{ mL} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$ , which was just slightly greater than  $3.5 \text{ mL} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$ .

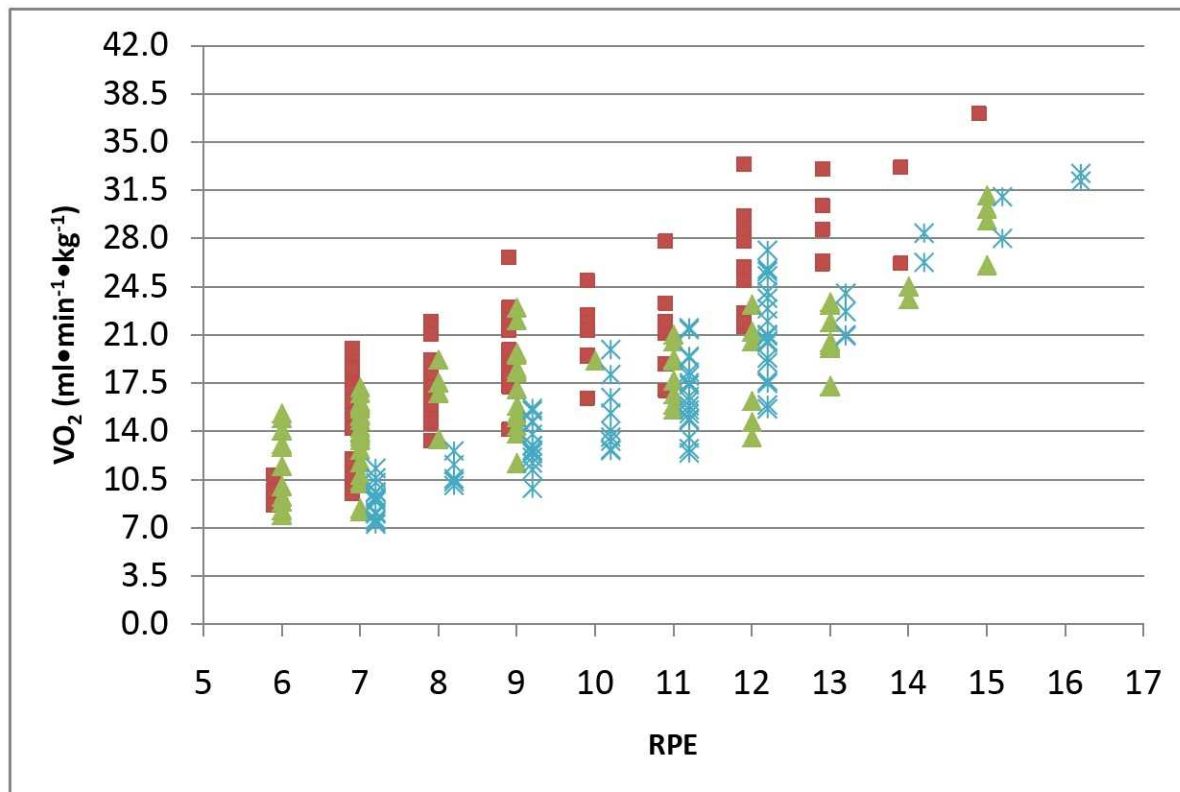


Figure 7.  $\text{VO}_2$  versus RPE for three different representative subjects



### 2.4.3 Earth Shirt-Sleeve Performance Index (ESSPI)

It would be desirable to develop a lunar EVA suit that required no more effort to perform a task than a person performing that same task on Earth without a suit. The Earth shirt-sleeve performance index (ESSPI) is defined as the metabolic cost of a lunar suited task divided by the metabolic cost of performing the same task under earth shirt sleeved conditions. The 1-g metabolic cost of an activity, specifically ambulation in this case, creates a reference point to compare suited data. The ESSPI then provides an index to identify which suited tasks may require the most improvement. To create the 1-g reference values, we used linear regression of our 1-g data set from the EWT and  $\text{VO}_{2\text{pk}}$  tests to predict metabolic rates for speeds above  $1.34 \text{ m}\cdot\text{s}^{-1}$ . For speeds below  $1.34 \text{ m}\cdot\text{s}^{-1}$ , we used the American College of Sports Medicine (ACSM) predictive equation (5).

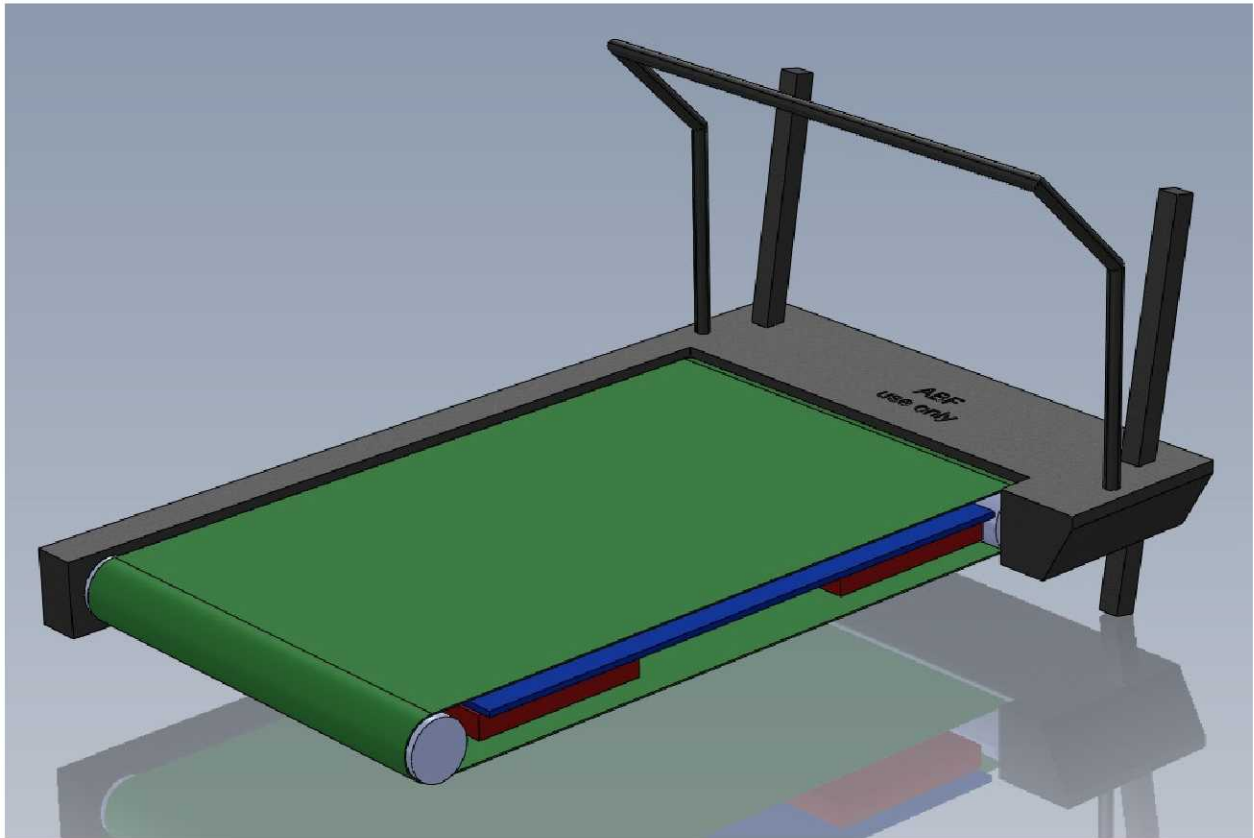
### 2.5 Biomechanical Data Collection and Analysis

Biomechanical data were collected using a 12-camera motion analysis system (Vicon MX Ultranets hardware, Vicon Nexus software [Vicon, Oxford Metrics, Oxford, UK]) and 4 strain-gauge force plates (AMTI, Watertown, MA). The force data were then processed and analyzed using customized MATLAB (The Mathworks, Inc., Natick, MA, USA) computer programs. Data were sampled during 30 full, consistent strides during each stage of testing.

Ground reaction forces were collected using  $46.2 \times 50.8 \text{ cm}$  force plates, mounted to each corner inside the treadmill and underneath the treadmill belt support plate (see Figure 8). The signal was collected at 1000 Hz over 30 gait cycles at varying speeds, pressures, and simulated suit weights and then stored for subsequent analysis. The vertical components of each of the four force-plates were resolved into one vertical component and summed together for each of the 30 gait cycles. For all trials, in each of the conditions, the peak vertical force was determined using customized MATLAB computer code over the 30 gait cycles.

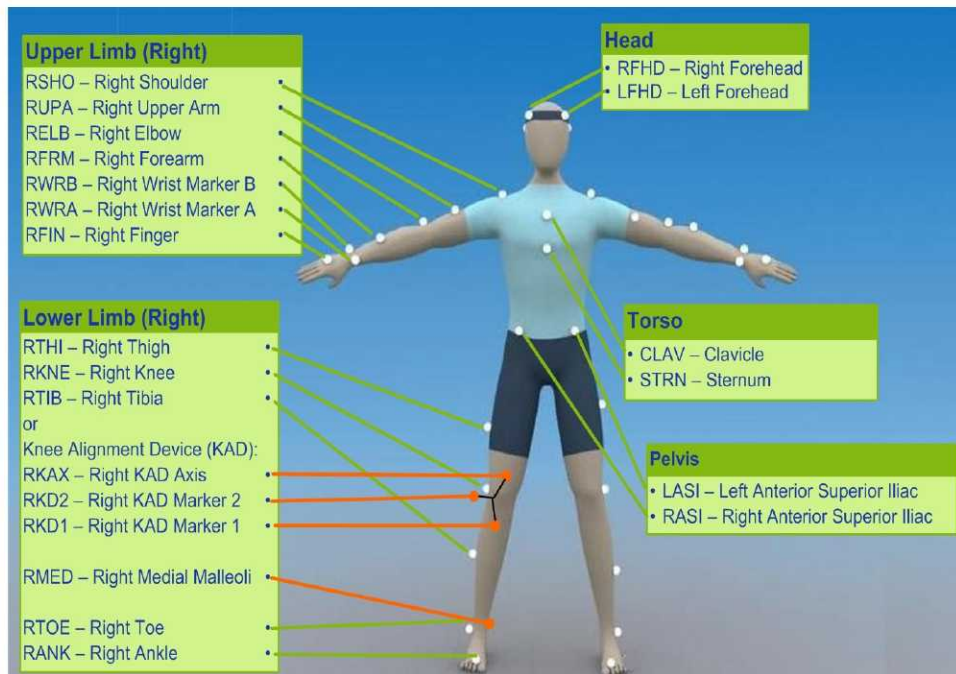
Three-dimensional trajectories of retro-reflective markers placed at approximate anatomical landmarks on the MKIII suit were collected at 100 Hz (Vicon, Oxford, UK) to determine the displacement of the segments of the suit. These trajectories were then filtered, processed, and reduced to the three-dimensional angular displacement of the three lower extremity joints during locomotion using customized computer code. This information was used for subsequent analysis to describe the kinematics of the MKIII suit during treadmill ambulation at varying suit pressures and weights.



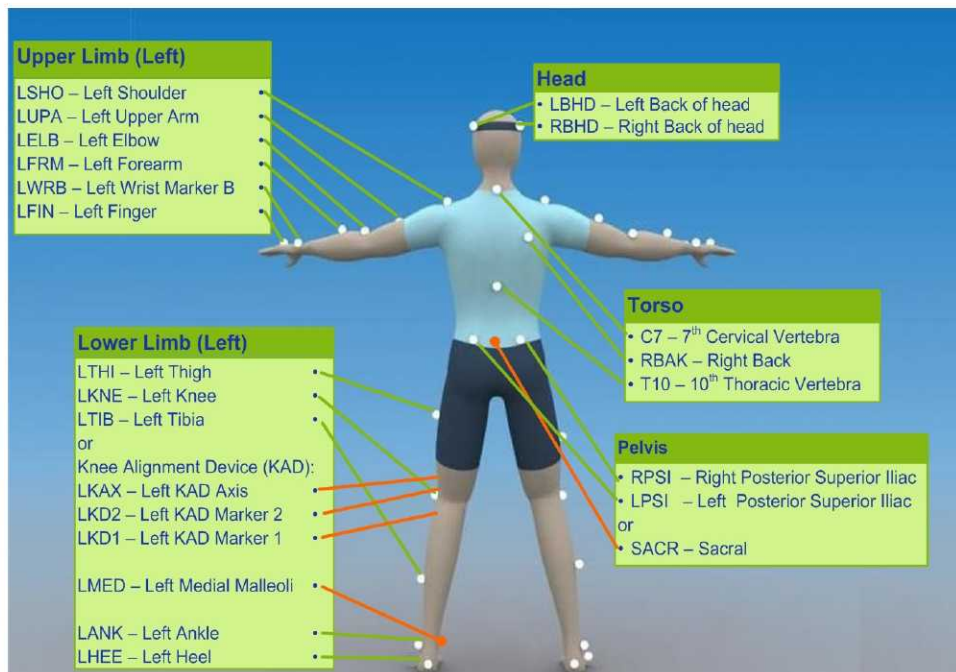


**Figure 8. Four force plates (red boxes) were mounted to each corner support structure of the treadmill underneath the treadmill belt**

The motion analysis system was used to record 3-dimensional trajectories of reflective markers, 51 in total, which was a modified Plug-in-Gait (VICON, Oxford Metrics, Oxford, UK) marker set (see Figure 9 and Figure 10), attached to each body segment of the subjects. The 3-dimensional trajectory data was reduced and analyzed using customized MATLAB computer programs to provide selected kinematic and temporal spatial characteristics of suited human locomotion.



**Figure 9. Anterior view of Plug-in-Gait marker set**



**Figure 10. Posterior view of Plug-in-Gait marker set**

In movements such as locomotion, the motions of the segments are cyclic in nature. More specifically, walking is the periodic movement of each foot from one position of support to the next. For walking, one stride (or cycle) is defined as the distance traveled by a person from one heel strike to the next heel strike on the same side. For analysis, each trial was subdivided into gait cycles. Information from each gait cycle was extracted and averaged assuming that constant gait was maintained.

## 2.6 Subjective Data Collection and Analysis

### 2.6.1 Self-Reported Subjective Data

The following subjective ratings were recorded at the end of each testing condition:

- The Gravity Compensation and Performance Scale (GCPS) was used to assess the level of compensation to maintain their performance as compared to their performance achieved while unsuited at 1-g (1).
- Ratings of Perceived Exertion (RPE) (6) were used to gauge how much effort subjects felt they must exert to complete each condition.
- The Corlett & Bishop Body Part Discomfort Scale was used to characterize discomfort at different body locations (7).
- Thermal comfort was assessed for two reasons: to determine the subjective thermal comfort of the subject and to determine whether any changes were necessary to improve the thermal comfort of the subject during testing. Thermal comfort was assessed using the Bedford scale (8).

Additional information on each of these scales is included in Appendix B. GCPS is a relatively new rating scale and as such will be compared with pertinent objective measures of compensation and performance throughout this test and others to determine the validity of the scale. In addition, GCPS will be used in conjunction with RPE to develop predictive models for metabolic rate with the intent that these subjective factors can be used in other lunar analog environments, such as underwater analogs and parabolic flight where direct measures of metabolic rate are currently not possible. Discomfort and thermal comfort were both primarily used for test termination criteria as well as to provide feedback to the test team about test hardware, conditions, and length of trials. Discomfort and thermal data will not be discussed in this report.

### 2.6.2 Significant Subjective Differences

In comparing the subjective ratings of different conditions, it is important to define some level of change that is deemed significant. Because of the limited sample size ( $n = 6$ ), inferential statistics were not used; therefore, statistical significance was not calculated. For these analyses a change in RPE of 2 was chosen for practical significance. RPE changes of one unit are approximately at the level of practical significance for  $\text{VO}_2$ , but because RPE is a whole number scale, it would take a change  $>1$  to see significant differences in metabolic rate. Further, the description of  $\text{VO}_2$  variability within a given RPE (Figure 7) demonstrated the large  $\text{VO}_2$  variability for a given RPE.

GCPS is not a continuously linear scale like RPE. Therefore, changes in GCPS are more complicated to assign a simple level of practical significance to. It is reasonable to define a range of GCPS, where changes within the range are interesting, but would not be considered to be practically significant. Using this breakdown, we selected a GCPS range of 1 to 3 as “ideal”, 4 as “acceptable”, 5 to 6 as “modifications warranted”, 7 to 9 as “modifications required” and 10 as “unable to complete task”. For some discussion, a value of 10 was lumped in with the 7 to 9 range as these would all be considered “unacceptable” performance. Full consensus within the team was not achieved on whether a value of 4 is more associated with the “ideal” range or the “modifications warranted” range. For the modeling data discussed in the following sections, it was included in the “modifications warranted” group, but for direct interpretation of the results, we’ve chosen a value of

4 to stand alone as its own category. Therefore, a level of practical significance for GCPS is one in which the value changes to a different category.

## 2.7 Imaging

Photographic data were collected after completion of each testing run if human-suit interactions were unfavorable or resulted in skin or musculoskeletal abnormalities. This information will be provided as feedback to the JSC's Space Medicine Division and EVA suit engineers. During all suited tests a digital video camera captured video of the subject in the sagittal plane as well as auditory comments of the crewmember and test team. During all unsuited tests video was captured without the audio.

## 3 PRELIMINARY RESULTS AND DISCUSSION

The results of IST-1 and their implications are discussed in this section. The section is separated into subsections corresponding to the test objectives described in Section 1.1. For each test objective, the results of the analyses performed to date are described; the potential implications of these results are discussed with respect to EVA suit requirements, design and concepts of operations; and the suggestions for further analyses or testing to meet the test objectives are described.

Before specific analysis of objectives is described, results pertinent to the interpretation of the data include the speed selection of the individual subjects and alignment of the gimbal axes of rotation with the system CG.

### Preferred Transition Speeds (PTS)

Table 3 describes the unsuited PTS at lunar gravity. Individual subject speeds were then based on the PTS as described in Table 2. Similar to results seen in the EWT (1), PTS did not agree with a predicted Froude number of 0.5 (9).

**Table 3. Unsuited PTS at lunar gravity**

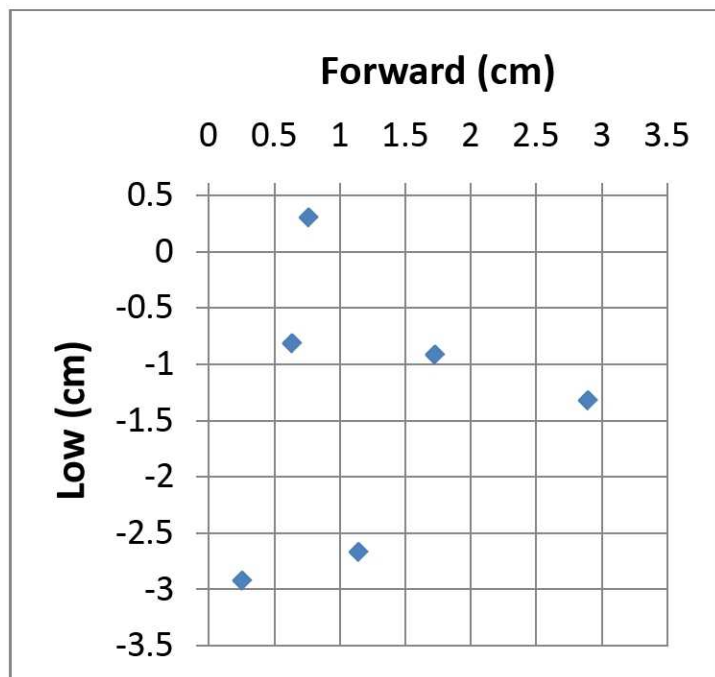
Subject	1/6-g Unsuited		
	PTS (m•s <sup>-1</sup> )	PTS (mph)	Froude
1	1.52	3.4	1.56
2	1.43	3.2	1.28
3	1.34	3	1.29
4	1.30	2.9	1.00
5	1.56	3.5	1.38
6	1.65	3.7	1.67
Mean ± SD	1.47 ± 0.14	3.3 ± 0.3	1.36 ± 0.23

### Location of System Center of Gravity

When assessing CG effects, there were 2 primary questions. The first was how the system CG lined up with the gimbal axes of rotation and the second was how the system CG differed from the subject's CG. Results of the second question were discussed in the EWT final report and state that the total system CG, which was based on a CAD model of the gimbal support structure, MKIII suit



and standard (182.9 cm, 81.6 kg) subject, differed from the subject's CG by 11.0 cm aft and 20.1 cm high when compared to the CG of a standard 182.9 cm, 81.6 kg CAD modeled subject (1). Regarding the first question, the location of the total system CG from the gimbal center of rotation averaged  $1.24 \pm 0.95$  cm forward and  $1.39 \pm 1.22$  cm low. As seen in Figure 11, 5 of 6 subjects selected this slight misalignment between the system CG and gimbal center of rotation that was forward and low with the remaining subject just slightly higher than 0 and forward as well.



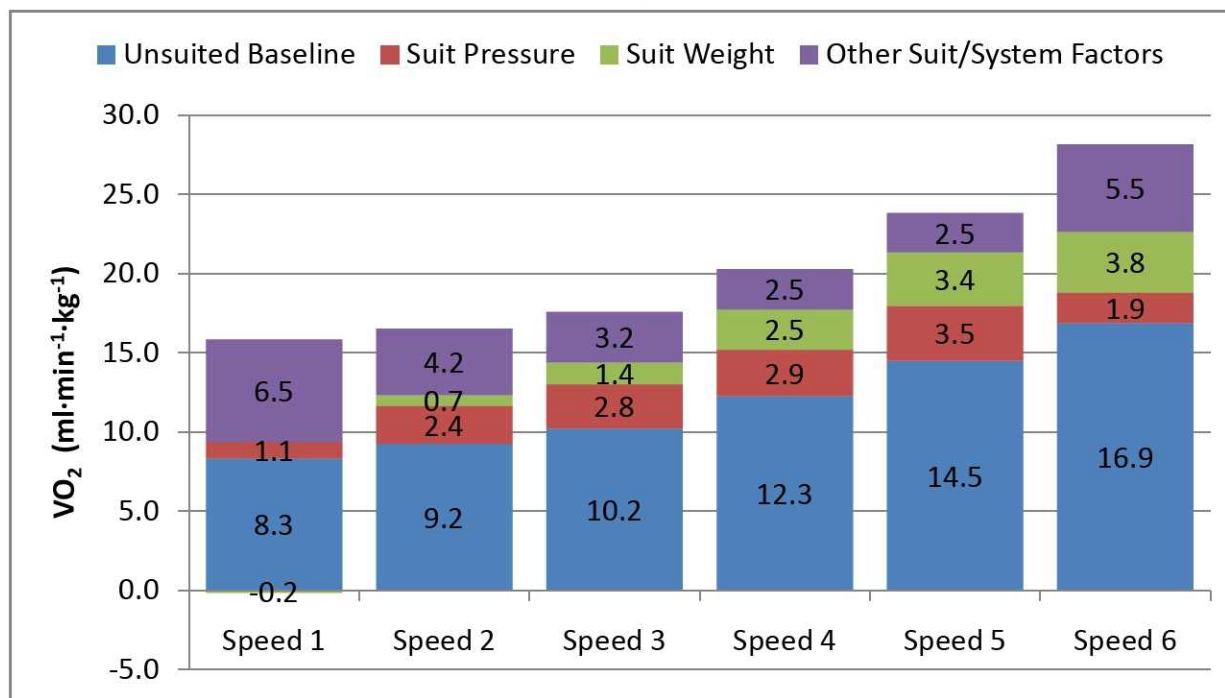
**Figure 11. Total system center of gravity location in relation to gimbal center of rotation**

### 3.1 Test Objective 1: Contributions of Weight, Mass, Pressure, and Suit Kinematics to Metabolic Cost of MKIII Suit POGO Configuration

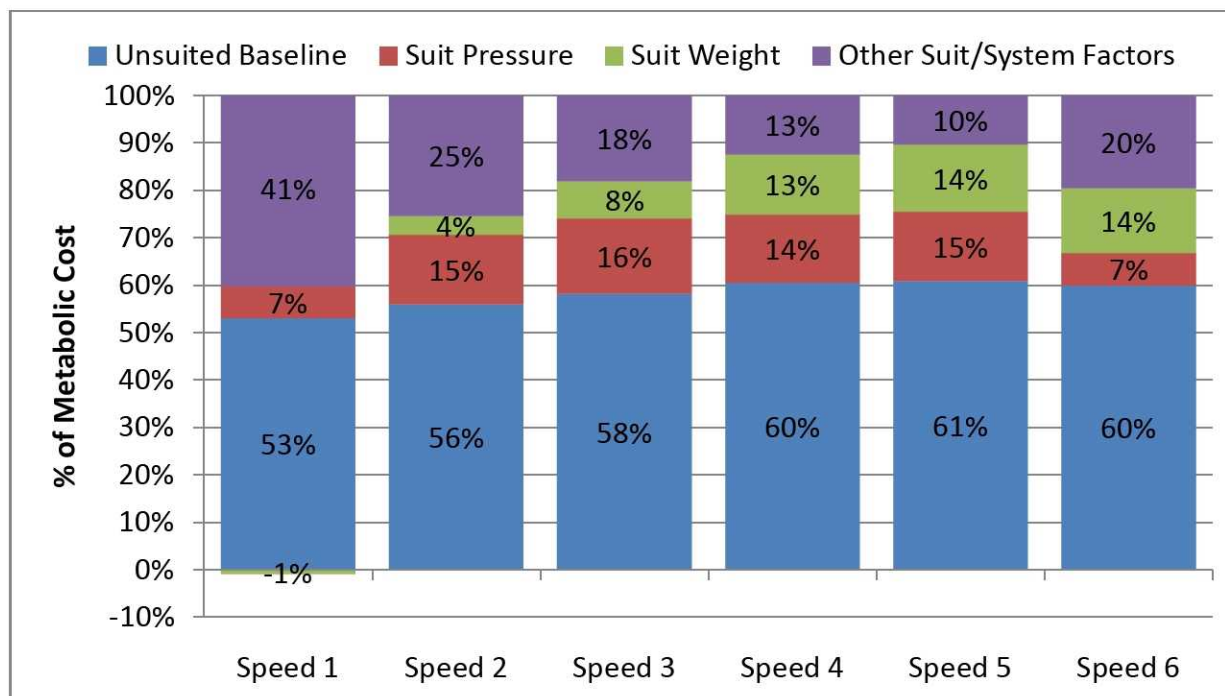
Test Objective 1 was “To identify the individual contributions of weight, inertial mass, pressure, and suit kinematics to the overall metabolic cost of the MKIII suit in its POGO configuration (121 kg [265 lb] including mass of portable life support system (PLSS) mockup and gimbal, 29.6 kPa [4.3 psi]) during lunar ambulation.”

The individual contributions of weight and pressure along with the combination of remaining components including mass, suit kinematics, stability, and system harness differences to the overall metabolic cost of the MKIII suit in POGO configuration are shown in Figure 12 (absolute cost) and Figure 13 (percentage cost). The methods for calculating the individual contributions are described in Section 0. In all cases, the baseline unsuited component accounted for the greatest percentage of total metabolic cost. The figures show that the overall metabolic cost of the MKIII suit in POGO configuration was the same for speeds 1 to 3 at  $7.3$  to  $7.6 \text{ mL} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$  and then increased to  $7.9$ ,  $9.4$ , and  $11.4 \text{ mL} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$  at speeds 4, 5, and 6 respectively. Although the trend was for the metabolic cost of the suit to increase in absolute terms, it actually decreased as a percentage of total suited metabolic rate as speeds increased. The results at speeds 1 and 6 were notably different from speeds 2-5, but likely because of different reasons. At speed 1, the increased weight of the suit seemed to have a positive effect on metabolic rate, but the slow speed may have required greater

starting and stopping of the added mass as well as the suit kinematic programming, which made the “other” category the largest. At speed 6, the other factors including greater ROM in all joints may have contributed to more travel and thus force required to stop the rotating components of the suit.



**Figure 12. Model for absolute metabolic cost of components comprising suited locomotion for the MKIII suit in POGO configuration in lunar gravity**



**Figure 13. Model for percentage metabolic cost of components comprising suited locomotion for the MKIII suit in POGO configuration in lunar gravity**

The unsuited baseline cost was consistently the largest component at about 60 percent of total metabolic cost and the other components were variable. The absolute cost of pressure-volume work at 29.6 kPa (4.3 psi) slowly increased from speeds 1 to 5, but dropped at speed 6. Outside of speeds 1 and 6, the percentage contribution of pressure-volume work accounted for about 15 percent of the total metabolic cost. It is not understood why the pressure-volume work cost was lower at the slowest and fastest speeds, but it could be that these speeds were outside of the optimal locomotion envelope for suited subjects because the contributions of the other suit/system factors were much higher indicating that something else (mass, stability, POGO interactions) was affecting suited metabolic rate.

The cost of weight steadily increased as speed increased, but the proportion of metabolic cost plateaued at 14 percent. As the cost of weight increased, the cost of the other factors decreased indicating that there are variable trends amongst the other factors.

Future tests will drive out the individual contributions of these remaining components, specifically mass and possibly suit kinematic constraints, as well as examine various inter-relationships and coupling factors present in untested combinations of these variables so that the recommendations are not only specific to the MKIII in POGO configuration. By understanding these individual factors, we will be able to provide specific recommendations for suit design requirements, EVA mission planning and overall consumables packaging.

A final important observation was that the metabolic cost of the suit did not change significantly (as defined in Section 2.4.2) over the expected range of nominal lunar locomotion speeds ( $\leq 1.5 \text{ m}\cdot\text{s}^{-1}$ ).

3.2 Test Objective 2: To quantify the effects of the following factors on suited and/or unsuited metabolic rate, biomechanics and subjective ratings during level ground ambulation at varied speeds:

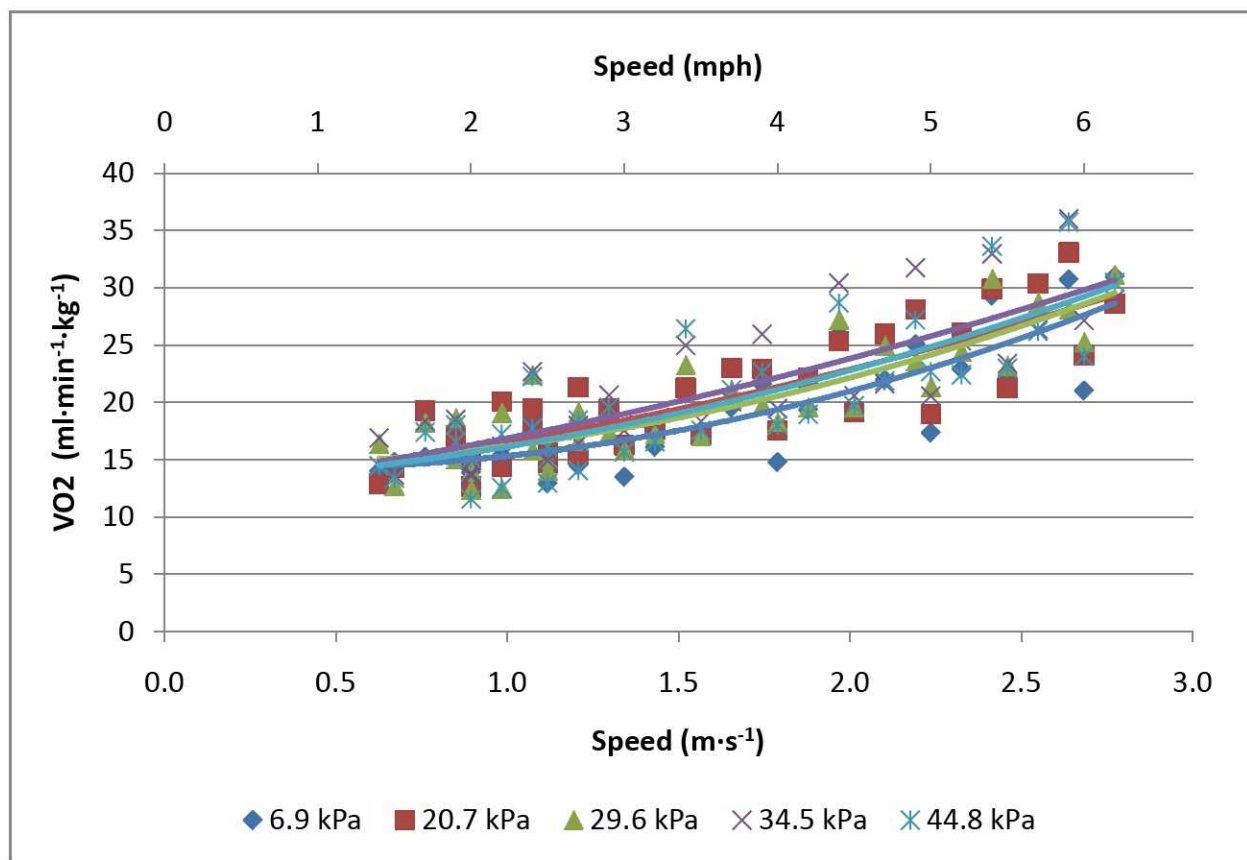
- a. Suited – varied suit pressure at constant offload, mass and CG
- b. Suited – varied suit offload (weight) at constant pressure, mass and CG
- c. Unsuited – varied offload (weight) at constant mass and CG
- d. Unsuited – varied mass at constant offload and CG

3.2.1 Effect of Varied Pressure at Constant Offload and Mass on Suited Human Performance

### **Metabolic Rate Findings**

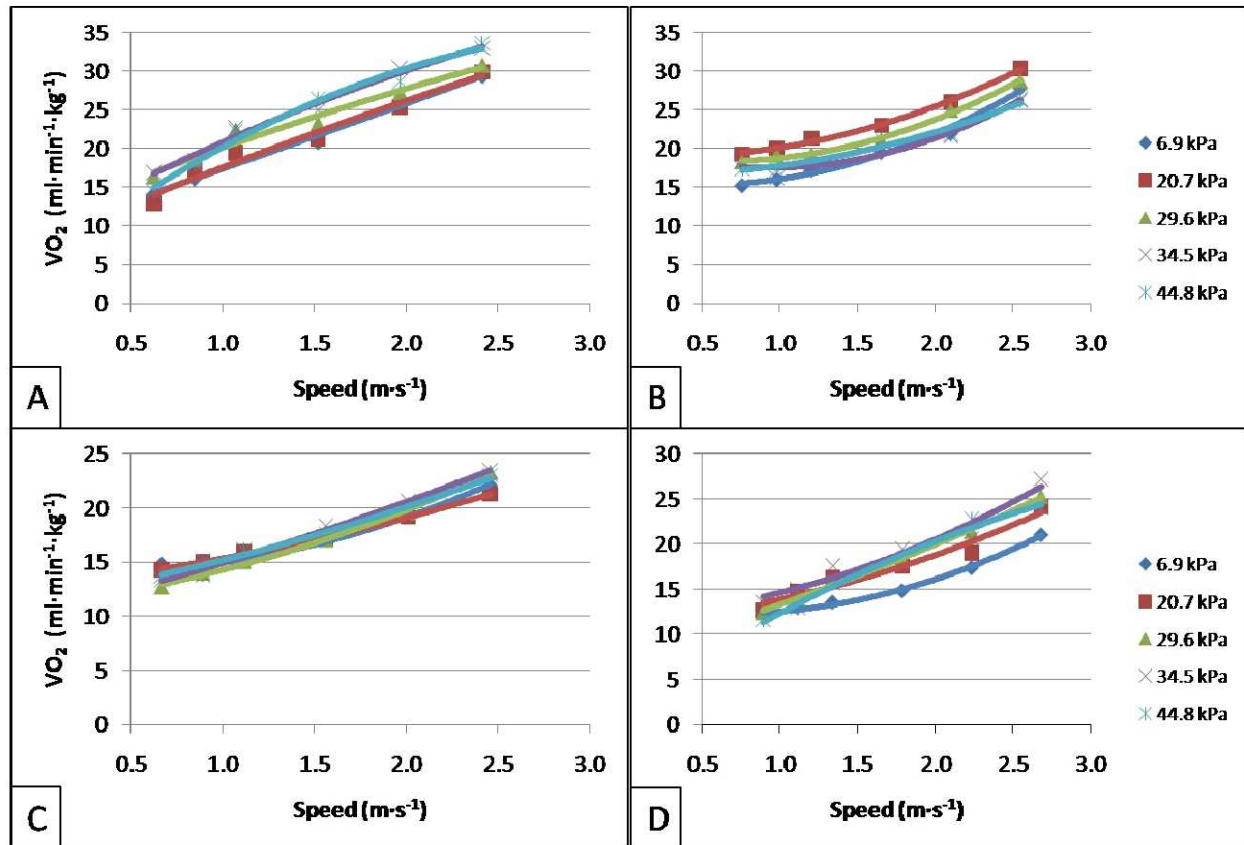
Variation in suit pressure at simulated lunar gravity did not significantly affect metabolic rate (see Figure 14). The largest difference was between 6.9 kPa (1.0 psi) and 34.5 kPa (5.0 psi) with the difference ranging from 0 to  $3.0 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$  across the range of speeds.





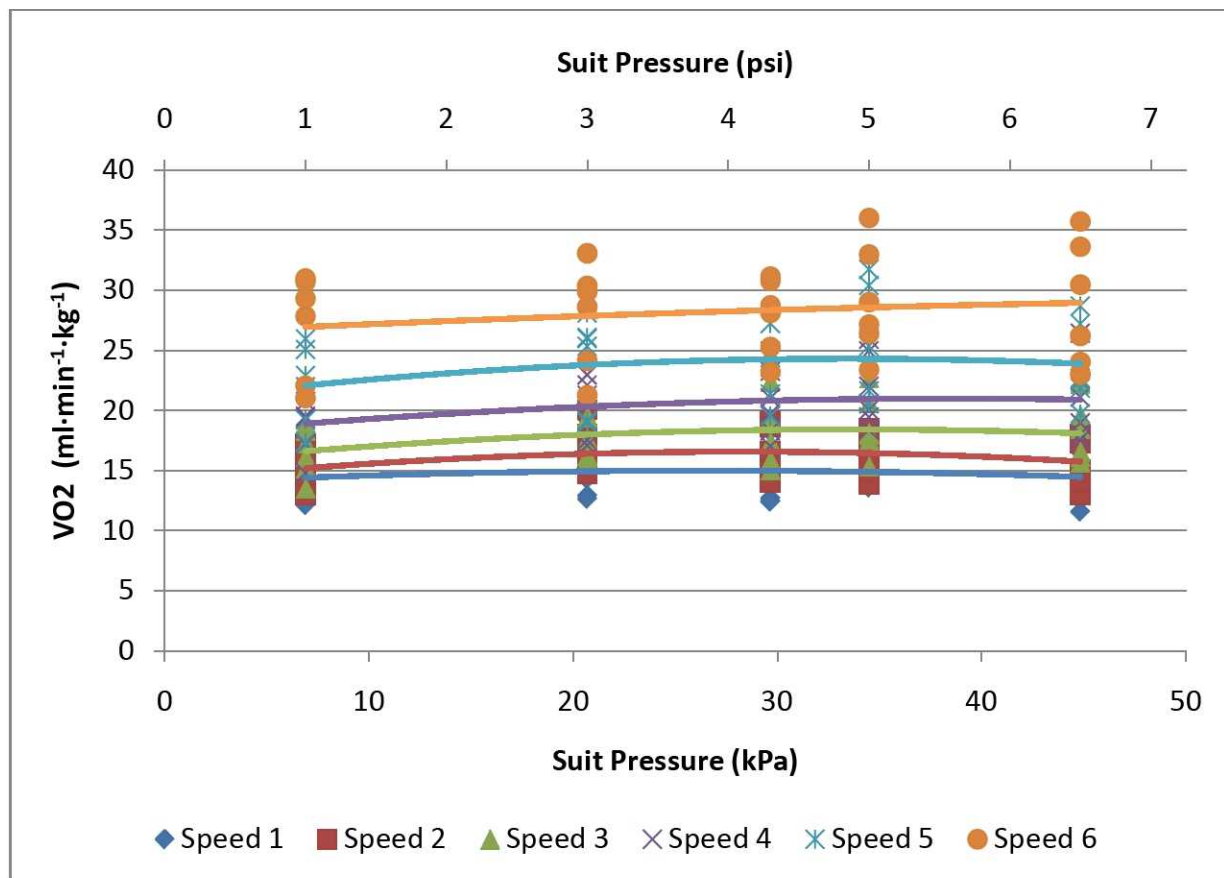
**Figure 14. Metabolic rate versus speed at different suit pressures during suited (121 kg) locomotion at lunar gravity**

While the average difference was not significant, (less than  $3.5 \text{ mL} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$ ), there was some variation between individual subject results ranging from higher metabolic rates at higher pressures (Figure 15A), to higher metabolic rates at lower pressures (Figure 15B) to almost no variation between pressures (Figure 15C) to results very similar to the overall mean (Figure 15D). The only truly consistent findings was that the 34.5 kPa (5.0 psi) trials led to the highest average metabolic rate in 5 of the 6 subjects and the 6.9 kPa (1.0 psi) trials led to the lowest metabolic rate in 4 of 6 subjects.



**Figure 15. Individual subject (A-D) metabolic rate responses to varied pressures at increased speeds**

Initially, there was a trend towards smaller subjects having lower metabolic rates at lower suit pressures and larger subjects having lower metabolic rates at higher pressures, but while this held true for our first 2 subjects, it did not continue for the remaining 4 subjects, nor was it supported by any significant differences in the biomechanics results. Carr and Newman showed in a comprehensive review of past studies how running might be more efficient than walking with one of the components of their model being pressure (2). Our initial hypothesis was that larger subjects could bend the suit legs with less effort because of the mechanical advantage of larger leg bending moments and possibly greater muscular strength. During the stance phase (the portion of a stride where the foot contacts the ground), the increased strength and mechanical advantage would allow these subjects to bend the knee more and store more energy elastically in the suit. The pressurized suit leg would essentially behave as an inflated beam, and once deflected, would have a tendency to recoil back to neutral position, with the recoil force being proportional to the inflation pressure. The degree of energy recovery would be proportional to the deflection of the knee and the suit pressure. This was a controversial hypothesis however, with members of the ABF disagreeing on the basis that the conservation of energy theorem, that the suit cannot add energy to the subject that was not already put into the suit by the subject. Therefore, the subject still has to do the work and thus there can be no assistance from the suit. Members of the suit element team also describe the knee joint as very close to constant volume, indicating that energy recovery because of the inflated beam theory is unlikely. Further analysis of biomechanics, anthropometry, and subject strength coupled with a larger subject pool would be needed to quantitatively evaluate this trend. Evaluation of another suit design that does not have a constant volume knee joint would also shed light on this issue.



**Figure 16. Metabolic rates within speeds at different suit pressures for suited locomotion at the 121 kg suit weight at lunar gravity**

Figure 16 shows there was very little variation in metabolic rate as a function of pressure for six different ambulation speeds, suggesting that metabolic costs are more related to ambulation speed than suit pressure. There was a drop in metabolic rate, from 20.7 kPa to 6.9 kPa, but it did not meet our significance criteria. This drop demonstrated that there was an increase in metabolic rate because of pressurization of the suit, but when an operationally relevant pressure (one that could sustain life in space) was achieved, there was little different from 20.7 to 44.8 kPa.

In summary, suit pressurization increases metabolic rate, but varying suit pressure within an operationally relevant range has minimal influence on the metabolic rate for the group as a whole. However, there is some evidence that pressure can be important within individual subjects for level ground ambulation because of the variability in individual responses. It is important to note that this test was limited to ambulation and does not imply that suit pressure would not have a significant effect on crewmembers performing upper body and hand intensive exploration tasks.

### Subjective Findings

Subjective findings showed similar trends to the metabolic rate. There was very little variation in either RPE or GCPS ratings between different suit pressures as shown in Figure 17 and Figure 18, respectively. RPE increased with speed as expected and closely mirrored the metabolic rate findings as seen in Figure 14. GCPS ratings slightly trended towards increasing with speed, but were generally between the ideal range of  $\leq 3$  and acceptable range of  $\leq 4$  for speeds 1 to 5, which



encompasses the range of nominal lunar suited ambulation speeds of  $<1.5 \text{ m}\cdot\text{s}^{-1}$ . GCPS ratings were all  $\leq 4$  for speeds 1 to 5. Only speed 6 had GCPS ratings above acceptable, which was likely because of the difficulty of ambulating at a fast run in the MKIII for some subjects.

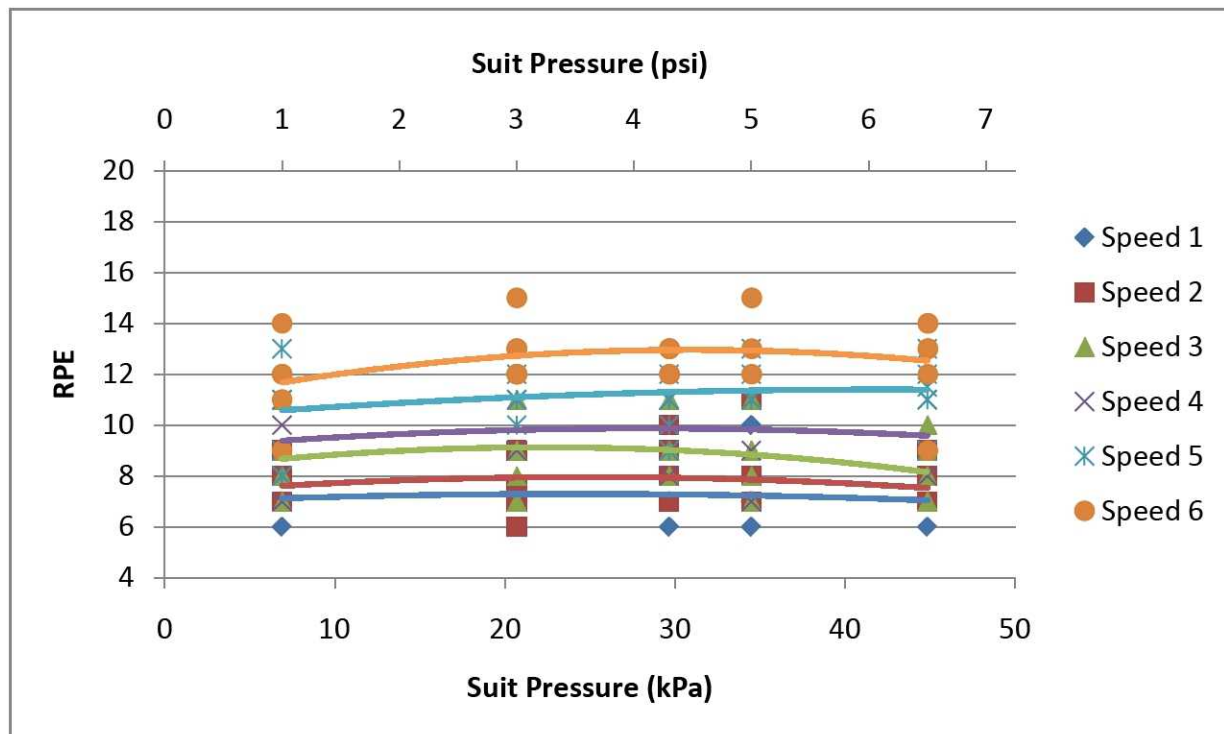


Figure 17. RPE at varied pressures for suited locomotion at the 121 kg suit mass in lunar gravity

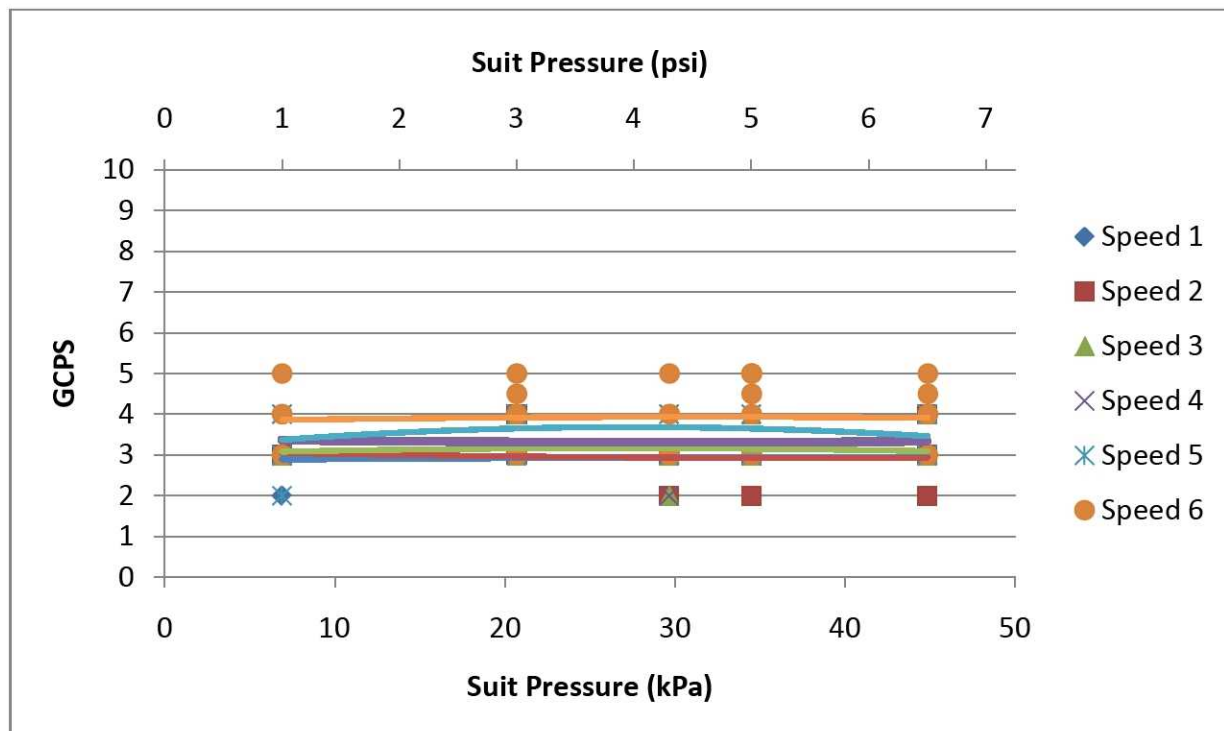


Figure 18. GCPS ratings at varied pressures for suited locomotion at the 121 kg suit mass in lunar gravity

## Biomechanics Findings

Changes in suit pressure exhibited minimal changes in selected biomechanical variables. Mean peak ground reaction force (GRF) increased with increasing speed but showed no observable trends with change in pressure. Temporal spatial gait parameters including percentage of stance time, step width, and cadence demonstrated no observable changes with changes in suit pressure. Similar to GRF the joint ranges of motion for the hip, knee, and ankle showed increases with increasing speed but there was no consistent effect in varying pressure (Figure 19–Figure 21).

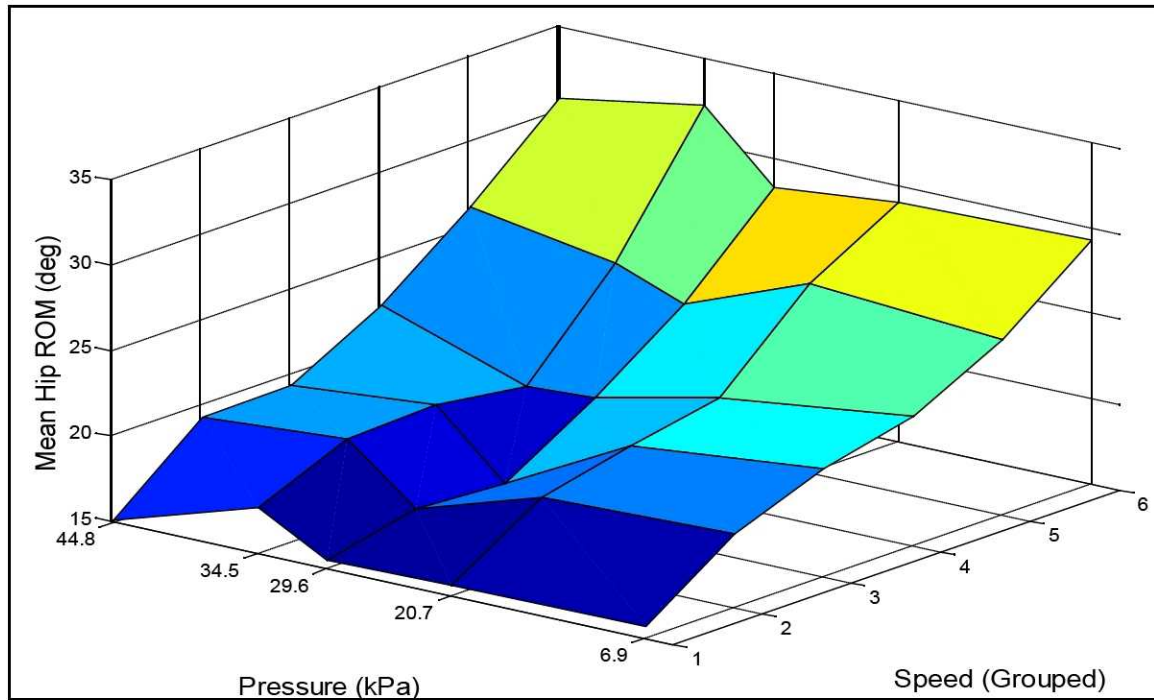
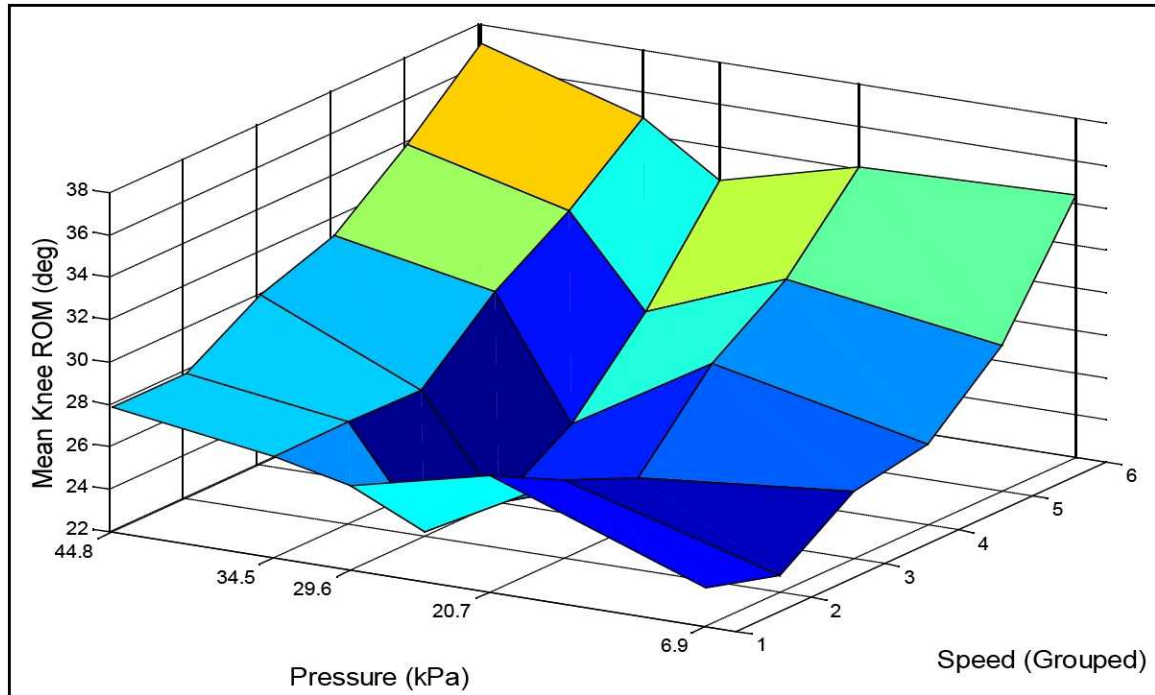
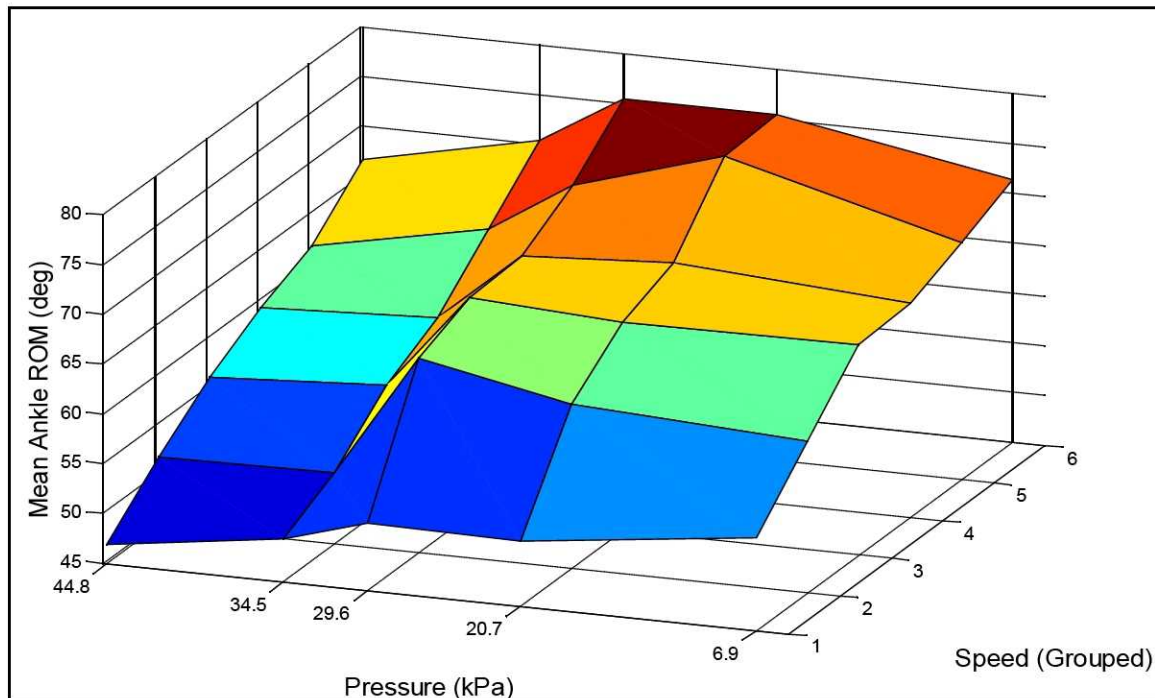


Figure 19. Hip ROM as a function of suit pressure and speed. The parametric colored surfaces represent the ROM value. The color scheme of warm to cool colors indicates the magnitude of the ROM value. The warmer colors (yellows, oranges, and reds) are the extreme values observed. Conversely, the cooler colors (blues) demonstrate the lower values observed.



**Figure 20. Knee ROM as a function of suit pressure and speed. The parametric colored surfaces represent the ROM value. The color scheme of warm to cool colors indicates the magnitude of the ROM value. The warmer colors (yellows, oranges, and reds) are the extreme values observed. Conversely, the cooler colors (blues) demonstrate the lower values observed.**



**Figure 21. Ankle ROM as a function of suit pressure and speed. The parametric colored surfaces represent the ROM value. The color scheme of warm to cool colors indicates the magnitude of the ROM value. The warmer colors (yellows, oranges, and reds) are the extreme values observed. Conversely, the cooler colors (blues) demonstrate the lower values observed.**

Further examination of the joint range-of-motion data demonstrate an anomaly that occurs at the 29.6 kPa pressure. The three-dimensional surface plots for the joint range of motion for both the hip and the knee demonstrate a “trough” at 29.6 kPa for all speeds. However, the ankle joint range of motion shows a “ridge” at 29.6 kPa for all speeds. More specifically, the ankle joint is being used to create larger ranges of motion while there is a decrease in ROM for the other joints as observed at this pressure across all speeds. This finding suggests that something is altering the gait kinematics at this pressure. This irregularity may be because of several factors including, but not limited, to POGO offloading mechanics, suit fit, experimental design, and/or suit kinematics at that pressure. Further study is warranted to understand this phenomenon. Given that the scope of the test did not allow for isolating all selected variables of interest, it is difficult to ascertain the cause of this trend observed in the data.

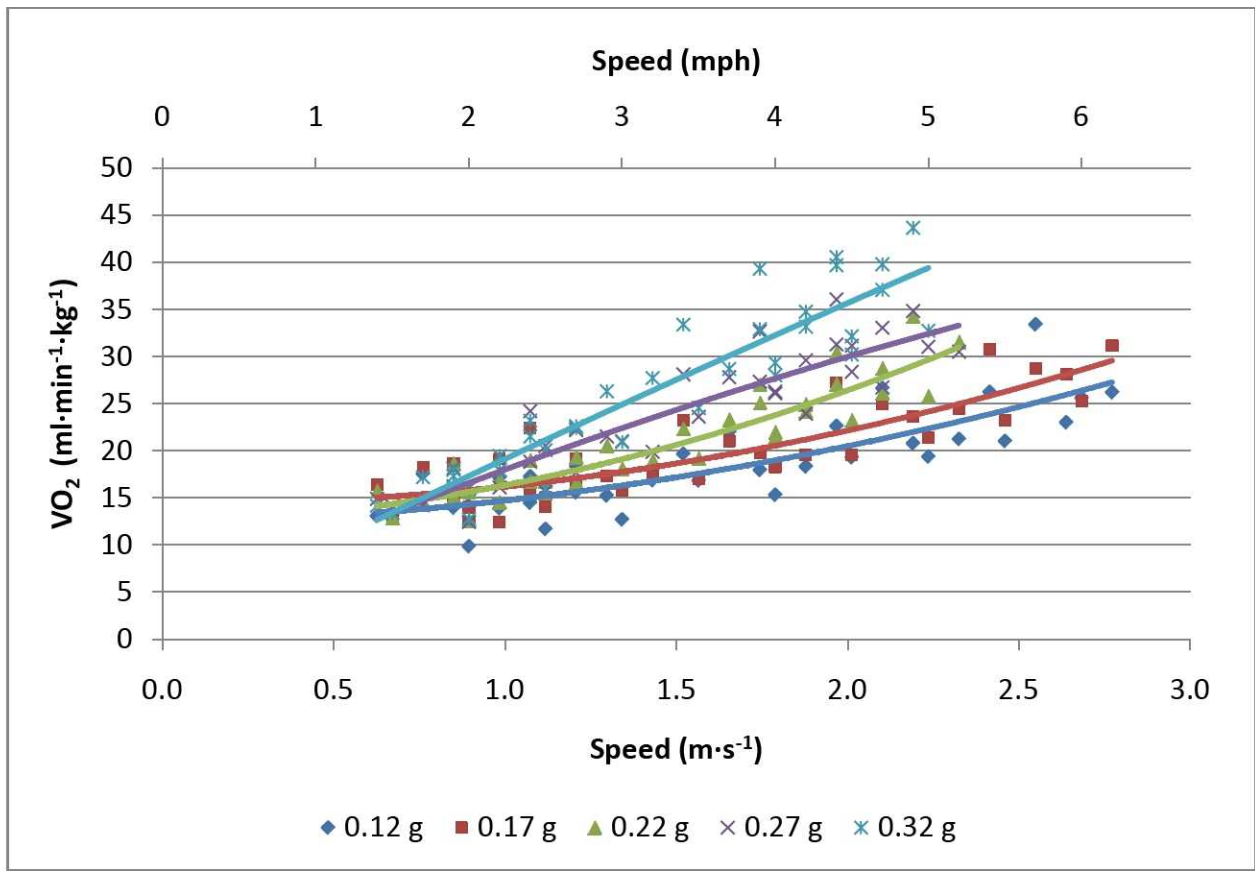
Overall, these findings suggest that as the suit pressure increases, the average joint ROM in the hip, knee, and ankle do not change significantly, which supports the observation that metabolic rate was essentially unchanged by suit pressure. Different suit designs with different joint designs and sequencing might be affected differently by suit pressure. For example, an entirely soft suit, such as the Advanced Crew Escape Suit (ACES) would likely have a very different joint ROM and metabolic cost in response to increasing pressure compared to the MKIII.

### 3.2.2 Effect of Varied Offload (Weight) at Constant Mass and Constant Suit Pressure on Suited and Unsuited Human Performance

#### Metabolic Findings

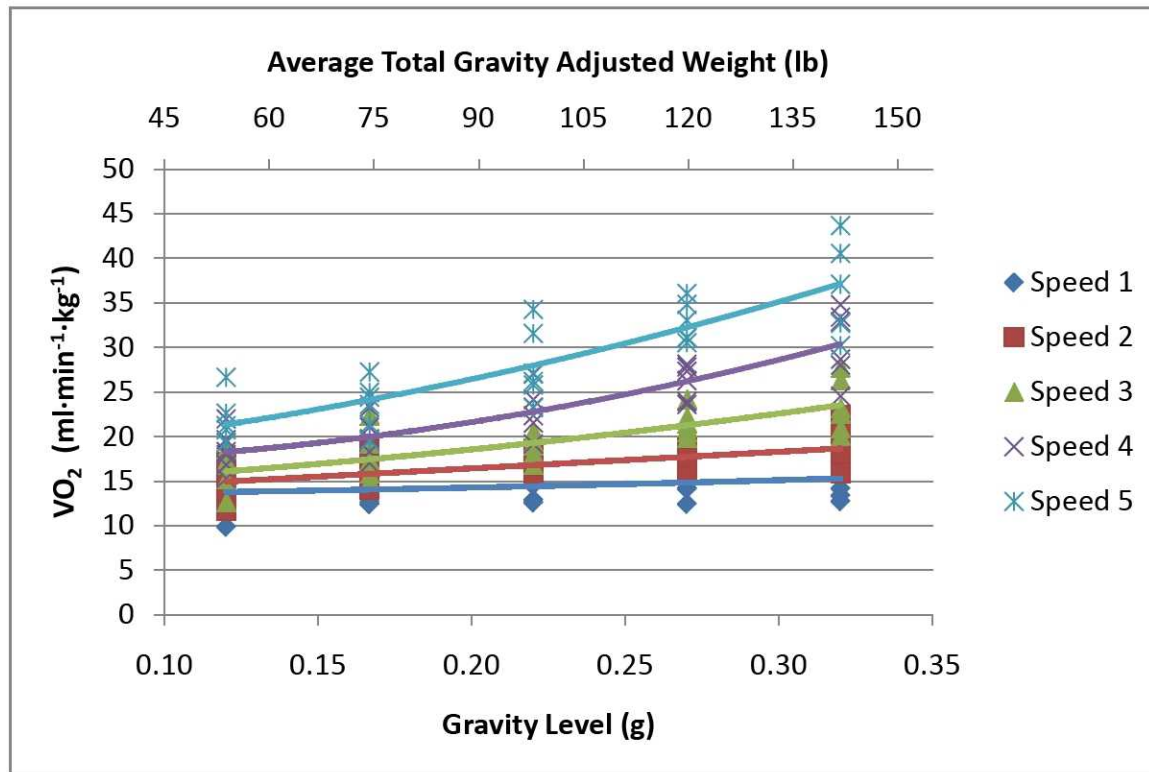
Figure 22 shows the relationship between metabolic rate and ambulation speeds for subjects in the MKIII at a constant suit mass of 121 kg and suit pressure (29.6 kPa) at varied gravity levels. At speeds less than  $1.0 \text{ m}\cdot\text{s}^{-1}$ , there was little difference in metabolic rate between gravity levels. The difference in average metabolic rate between the lowest and the highest gravity levels for speeds less than  $1.0 \text{ m}\cdot\text{s}^{-1}$  was  $2.03 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ , which was not significant ( $\leq 3.5 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ ). As speed increased beyond  $1.0 \text{ m}\cdot\text{s}^{-1}$ , the differences between gravity levels was more apparent. Between any two adjacent gravity levels, the differences were not significant until running speeds of  $2.0 \text{ m}\cdot\text{s}^{-1}$  or greater, where differences between 0.17 and 0.22-g and 0.27 and 0.32-g were most noticeable. At speeds above  $1.0 \text{ m}\cdot\text{s}^{-1}$  the differences in suit gravity level became significant. The difference between the lowest and the highest gravity level varies from  $\sim 7 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$  at speeds between  $1.0\text{-}1.5 \text{ m}\cdot\text{s}^{-1}$  up to  $\sim 14 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$  at speeds between  $1.5$  to  $2.0 \text{ m}\cdot\text{s}^{-1}$ .





**Figure 22. Metabolic rate versus speed at different gravity levels during suited locomotion at a constant mass (121 kg) and pressure (29.6 kPa)**

To better understand the suit related factors that cause an increase in metabolic rate with increasing weight, we compared the suited metabolic rates to the metabolic rates of weight-matched unsuited subjects. Figure 23 shows the relationship between metabolic rate and gravity level or TGAW for five different ambulation speeds with suited subjects. The effect of increasing weight is most apparent at higher speeds that would be seen during site to site translation or during an emergency walkback. These differences were almost negligible at the 2 lowest speeds, which would be associated with the intrasite translation speeds most likely to be seen during lunar EVA.



**Figure 23. Metabolic rate versus gravity level or average total gravity adjusted weight during suited locomotion with a constant suit pressure (29.6 kPa) and suit mass (121 kg)**

Figure 24 shows the same relationships with weight-matched unsuited subjects. Although weight alone does account for an increase in metabolic rate, it made up a smaller portion than expected. At the first 4 speeds, there is little change in metabolic rate for the unsuited weight-matched subjects even though their TGAW almost doubles from 74 to 143 lb.

Subtracting the metabolic rates of the unsuited weight-matched control trials from the metabolic rates of the suited trials resulted in the metabolic cost of the suit that is not directly related to the increased weight and is comprised of factors such as inertial mass, kinematic constraints of the suit and possibly stability issues. Figure 25 is a plot of the difference in metabolic rate between suited and unsuited weight-matched subjects, as a function of gravity level or TGAW. This difference was significant for all speeds with the first two walking speeds showing little to no increase as gravity increased, but with the faster walking speeds and running speeds clearly showing an increase as gravity level increased, indicating that interactions between weight and speed exist that were not fully understood

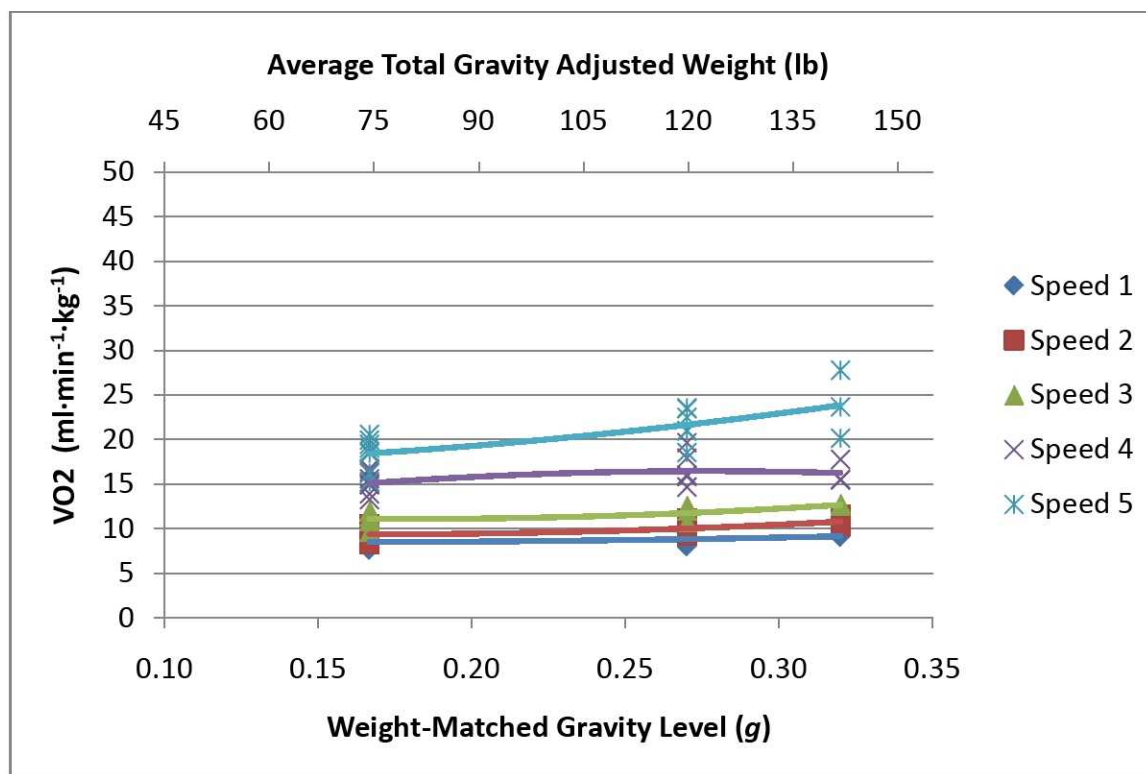


Figure 24. Metabolic rate versus weight-matched gravity level or average total gravity adjusted weight during unsuited locomotion with constant mass

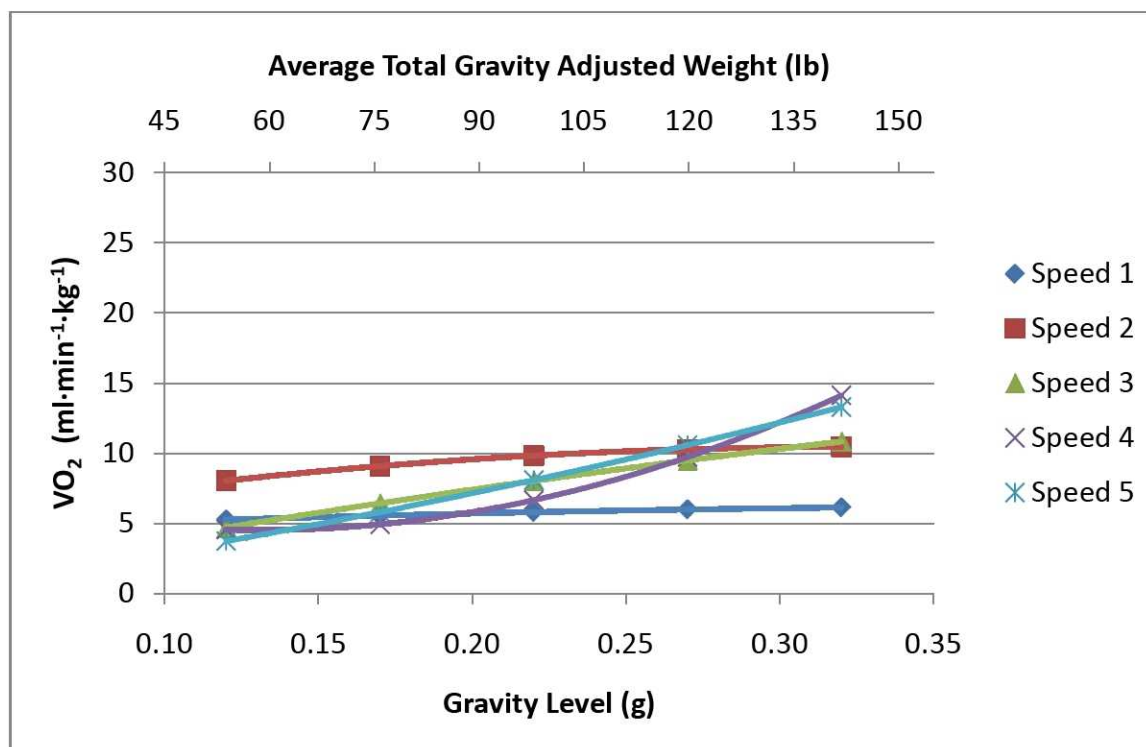


Figure 25. Metabolic cost of the suit not related to weight versus gravity level at a constant suit pressure of 29.6 kPa and suit mass of 121 kg

## Oxygen Transport Cost

Transport cost is defined as the volume of  $O_2$  required to translate 1 kg of body mass the distance of 1 km. It can be thought of as the equivalent of gas mileage. Results are shown in Figure 26. At speeds less than  $0.8 \text{ m}\cdot\text{s}^{-1}$ , the results are mixed and gravity level was not a discriminator of transport costs. The transport cost at gravity levels from 0.12 to 0.22-g were similar up to speeds of approximately  $1.5 \text{ m}\cdot\text{s}^{-1}$ , the upper end of nominal translation speeds. The two lowest gravity levels showed a continued decrease in transport cost through  $2.2 \text{ m}\cdot\text{s}^{-1}$ . Interpretation of these data in terms of suit mass on the Moon would indicate that a suit mass of 186 kg or less may be necessary for an efficient 10 km walkback contingency. These data suggest that the most efficient walkback speed range for a 186 kg suit might be 1.4 to  $2.1 \text{ m}\cdot\text{s}^{-1}$ , and the most efficient walkback speed for a 63 to 121 kg suit might be 1.8 to  $2.6 \text{ m}\cdot\text{s}^{-1}$ , although many factors may affect this selection including cooling limitations (1), terrain (10) as well as an understanding of how similar a change in TGAW from just an alteration in weight represents a true change in suit mass.

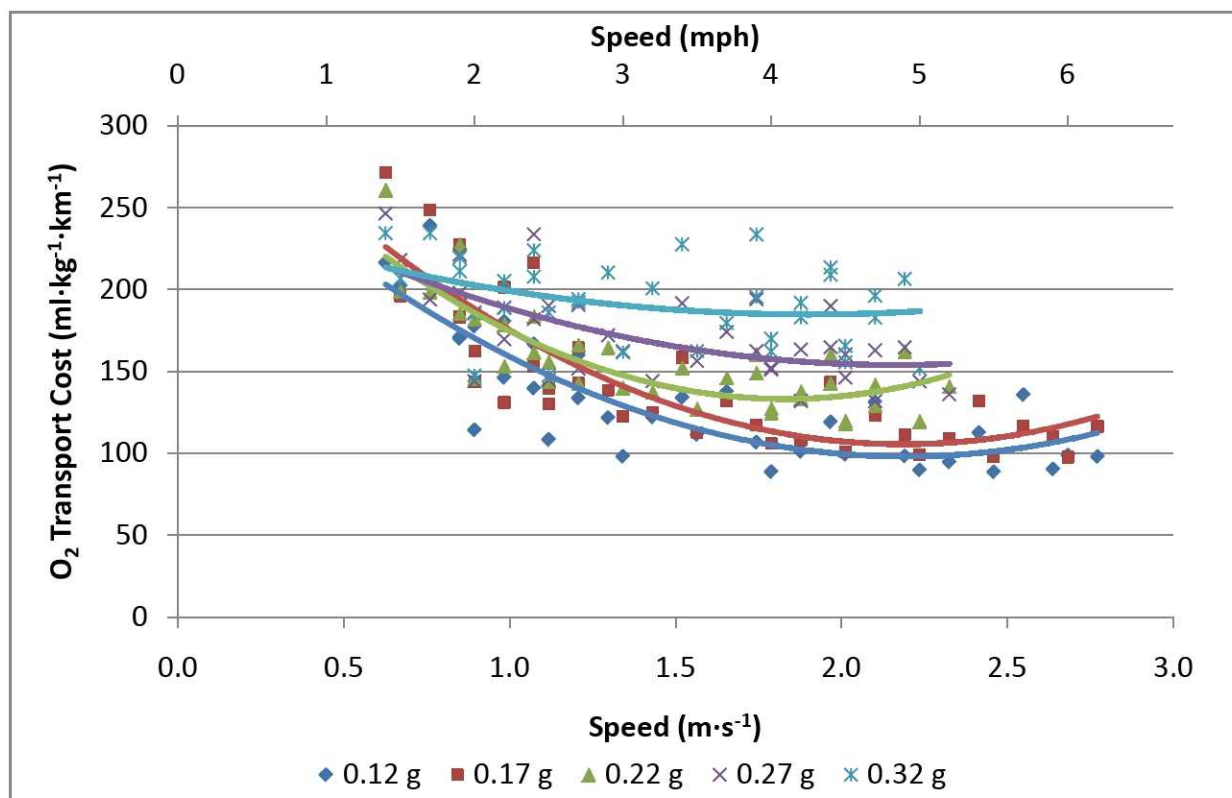


Figure 26. Transport cost versus speed at different gravity levels during suited locomotion at a constant mass (121 kg) and pressure (29.6 kPa)

## Subjective Findings

Subjective findings showed similar trends to the metabolic rate. The general trend as seen in Figure 27 was that RPE increased as gravity level increased. The difference in RPE between suit weights also increased as speed increased. RPE results were especially similar to the metabolic rate results, which indicate that the subjective RPE data is aligning well with the objective  $VO_2$  data and that in certain reduced gravity analogs where metabolic rate cannot be easily collected, the use of RPE may provide a good indication of performance differences. Figure 28 shows that GCPS ratings were very similar for gravity levels  $\leq 0.22$ -g at all speeds and were similar at all gravity levels for the two



lowest speeds. For the three highest speeds at the two highest gravity levels, the GCPS was higher by 1 to 3 levels. For all subjects at all speeds at gravity levels of  $\leq 0.22$ -g had GCPS ratings  $\leq 5$ , with most in the ideal range of  $\leq 3$ . In many cases, the heavier weights were also acceptable, but there were several ratings  $\geq 6$ , especially at higher speeds.

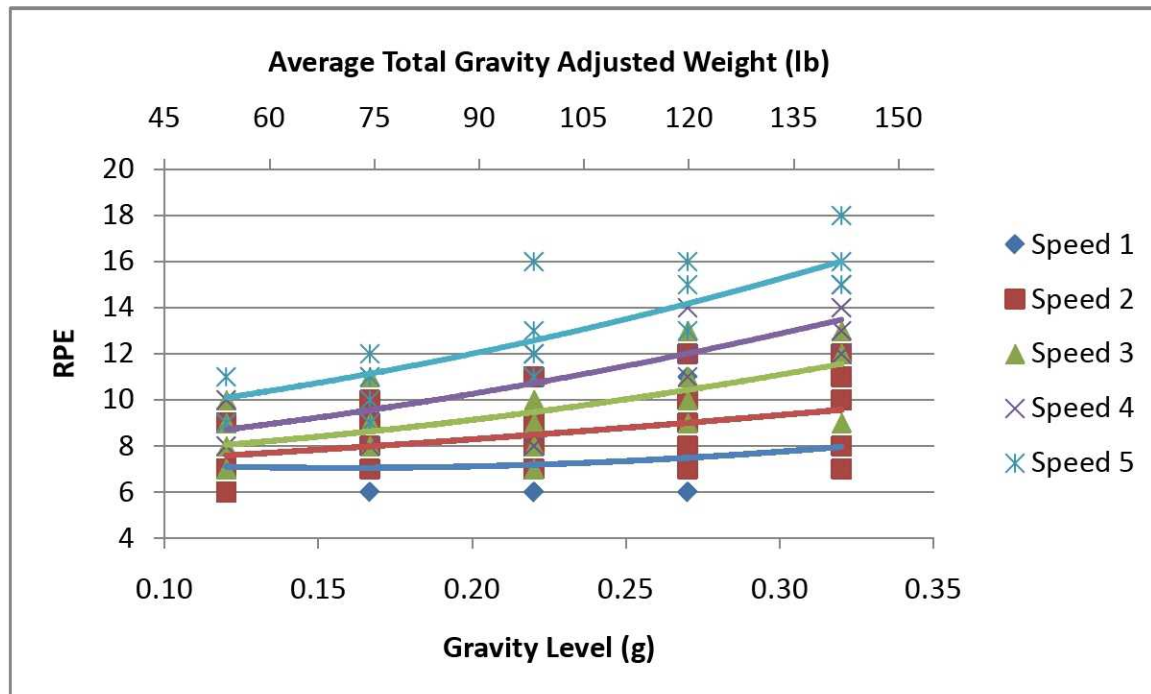


Figure 27. RPE versus gravity level or average TGAW during suited locomotion with a constant suit pressure (29.6 kPa) and suit mass (121 kg)

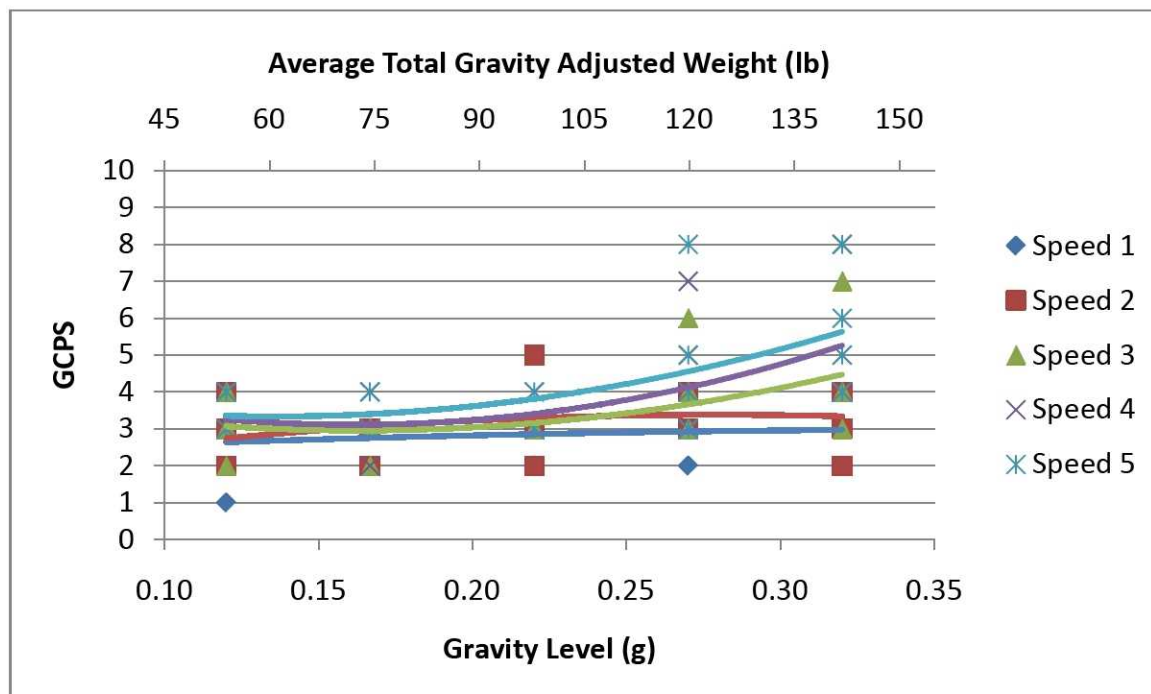


Figure 28. GCPS versus gravity level or average TGAW during suited locomotion with a constant suit pressure (29.6 kPa) and suit mass (121 kg)

## Biomechanics Findings

The ground reaction force is a result of the human interacting with the ground. During locomotion, the individual is acted upon by the GRF at the same time the individual pushes against the ground. The magnitude of the GRF varies as a function of locomotion speed, increasing with increasing speed. In earth walking, the vertical component of the GRF has a maximum value of 1 to 1.2 “times body weight” (BW) and in earth running, the maximum or peak can be as high as 3 to 5 BW (11) (12).

The mean vertical peak GRF versus gravity level is shown in Figure 29. Unlike varying the suit pressure, there appears to be a general trend of increasing vertical peak GRF, with increasing gravity. This trend was expected because of the increase in weight as gravity increased. There is also a clear trend that GRF increased as speed increased, also as expected. For expected nominal lunar ambulation speeds (speeds 1 to 3) the average GRF did not exceed 1.5 BW even at the heaviest conditions. Only with the increased weight seen at the higher gravity levels and faster running speeds did the GRF approach BW values seen during 1-g running. Although these data are encouraging from a bone and muscle preservation perspective, they still indicate that additional exercise countermeasures may be necessary and EVA alone may not be enough.

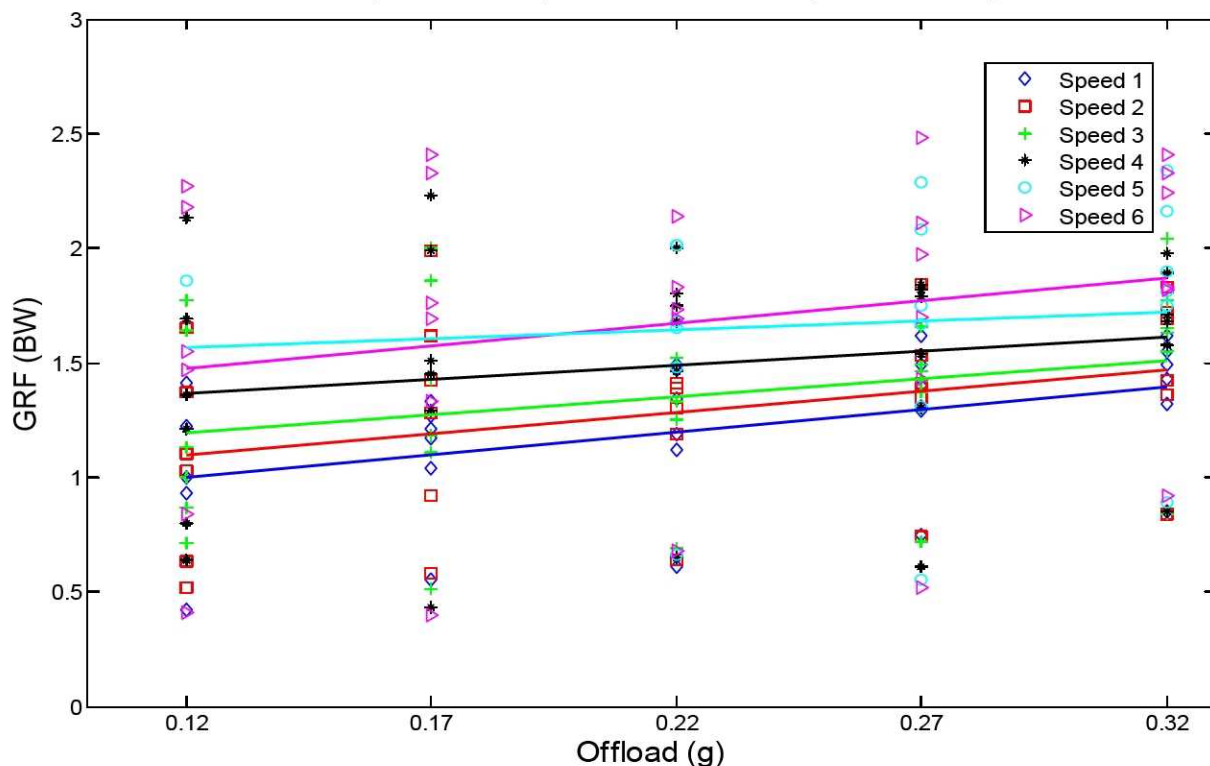


Figure 29. Peak GRF versus gravity level during suited locomotion with a constant suit pressure (29.6 kPa) and suit mass (121 kg)

Figure 30 and Figure 31 show that as gravity increased there was an increase in percentage stance time and cadence, respectively, for all locomotion speeds. Together, these data indicate that as gravity increased, subjects spent more time in contact with the ground and used shorter, more frequent strides to compensate for the increased weight.

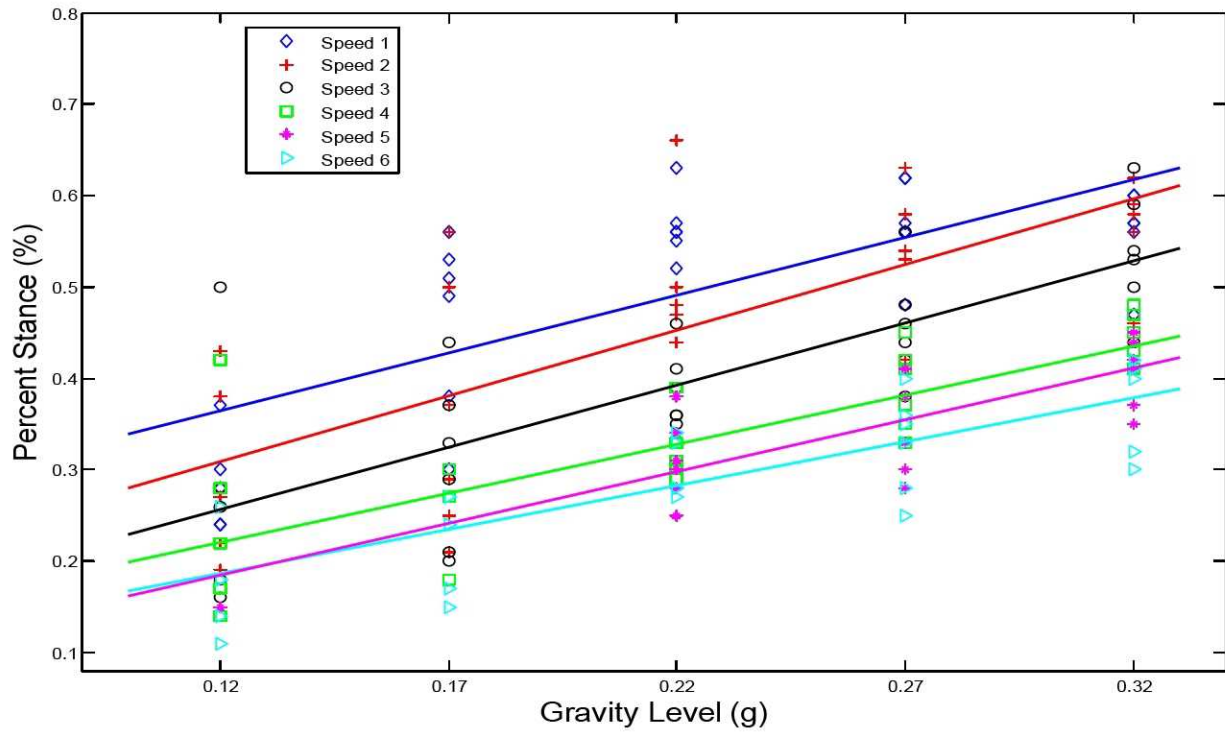


Figure 30. Stance time versus gravity level during suited locomotion with a constant suit pressure (29.6 kPa) and suit mass (121 kg)

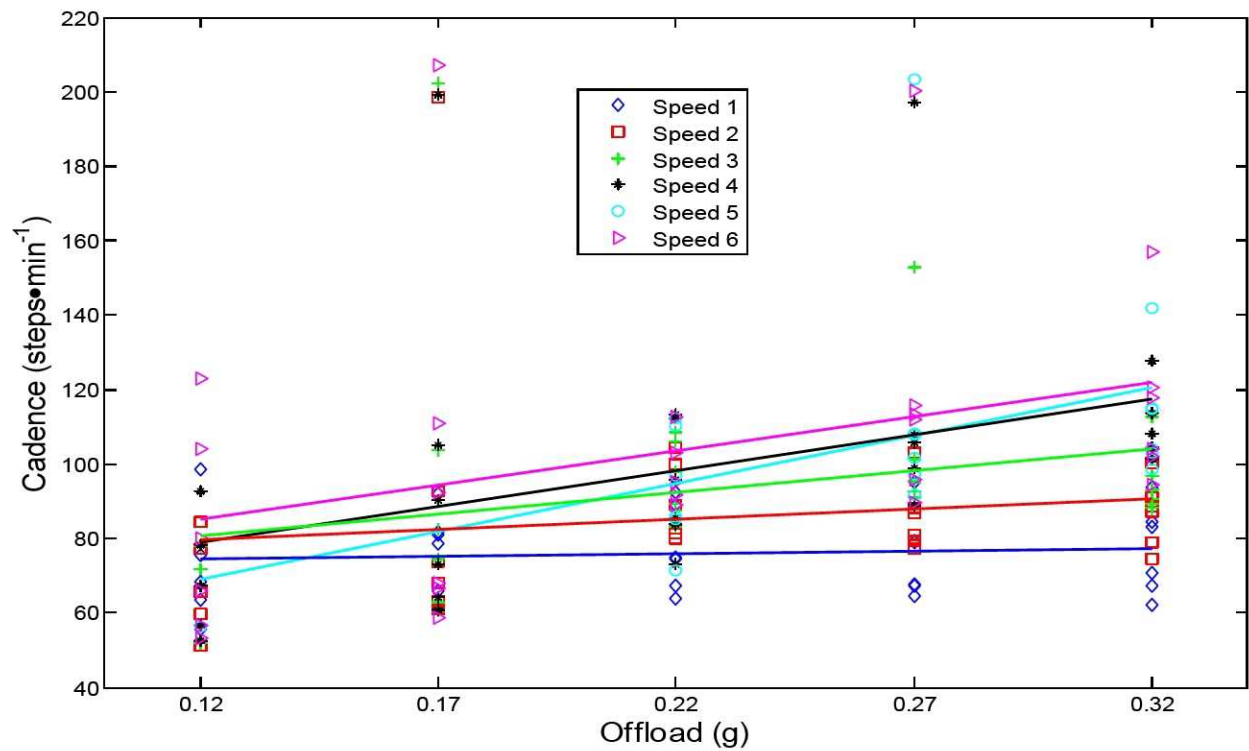
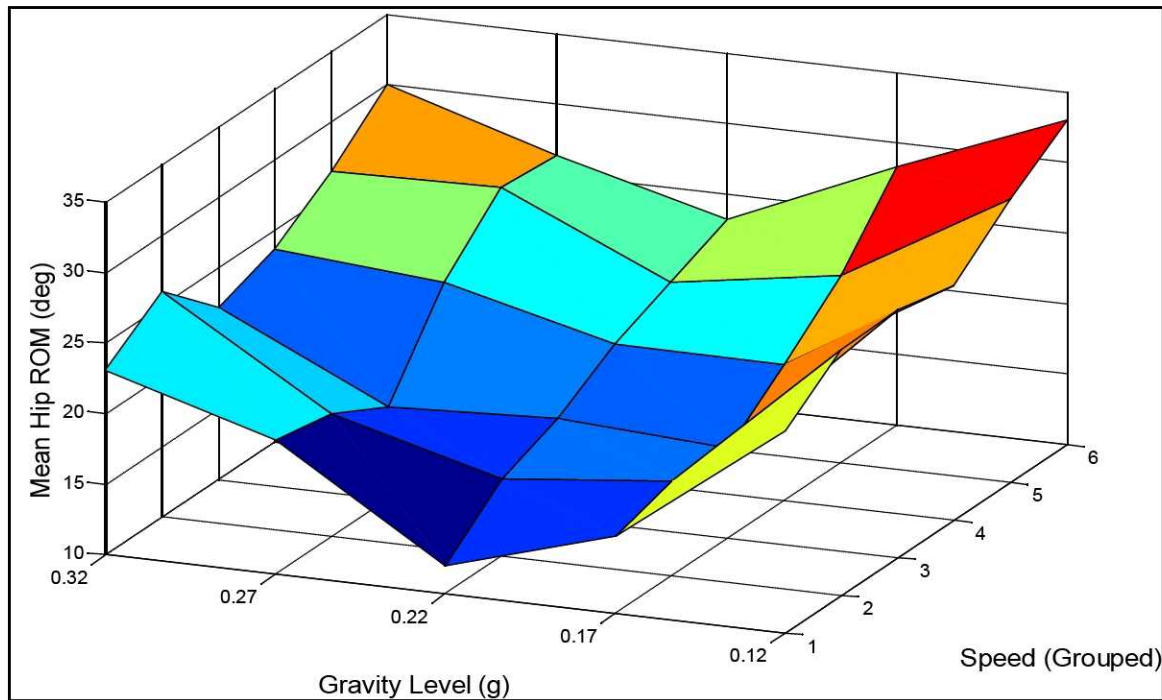


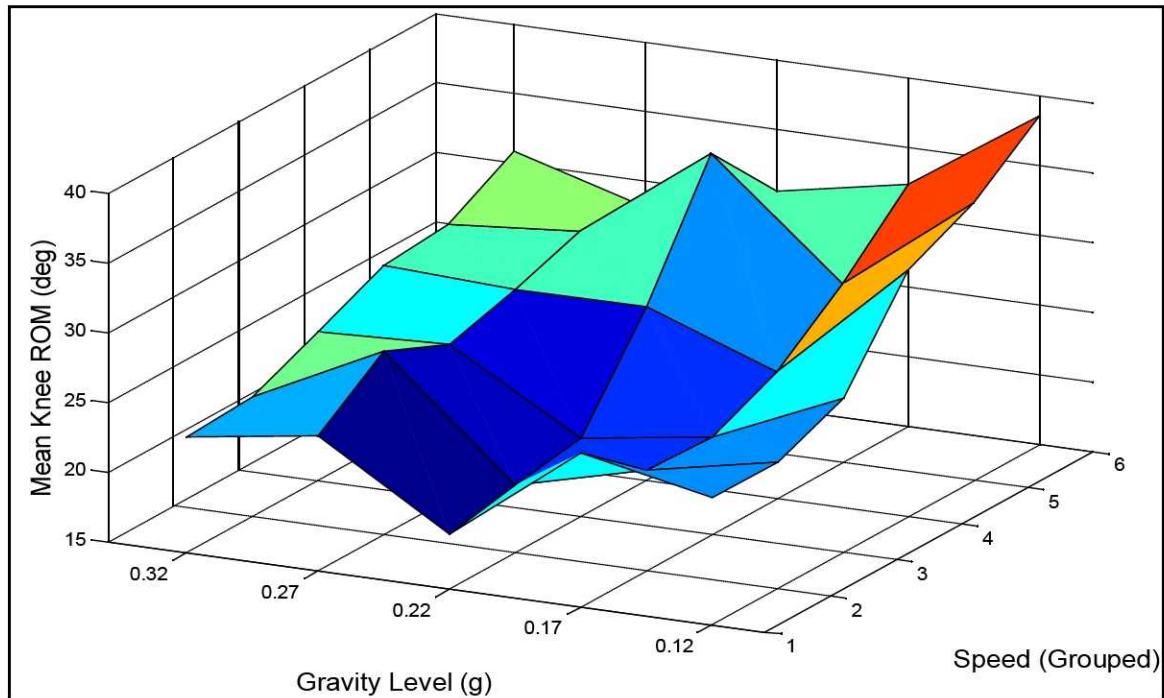
Figure 31. Cadence versus gravity level during suited locomotion with a constant suit pressure (29.6 kPa) and suit mass (121 kg)

The mean hip, knee, and ankle ROM exhibited an abnormality at 0.22-g similar to the ROM data for varying pressure (Figure 32-Figure 34). The hip and ankle ROM data at 0.22-g appears to have a “trough” across all speeds. The knee ROM at 0.22-g shows a trough across the first 2 speeds but then demonstrates a ridge for the remaining speeds. This suggests that gait kinematics are being altered at this offload. The deviation may be because of the same factors discussed in the varying pressure section and further study would be needed to understand this phenomenon.

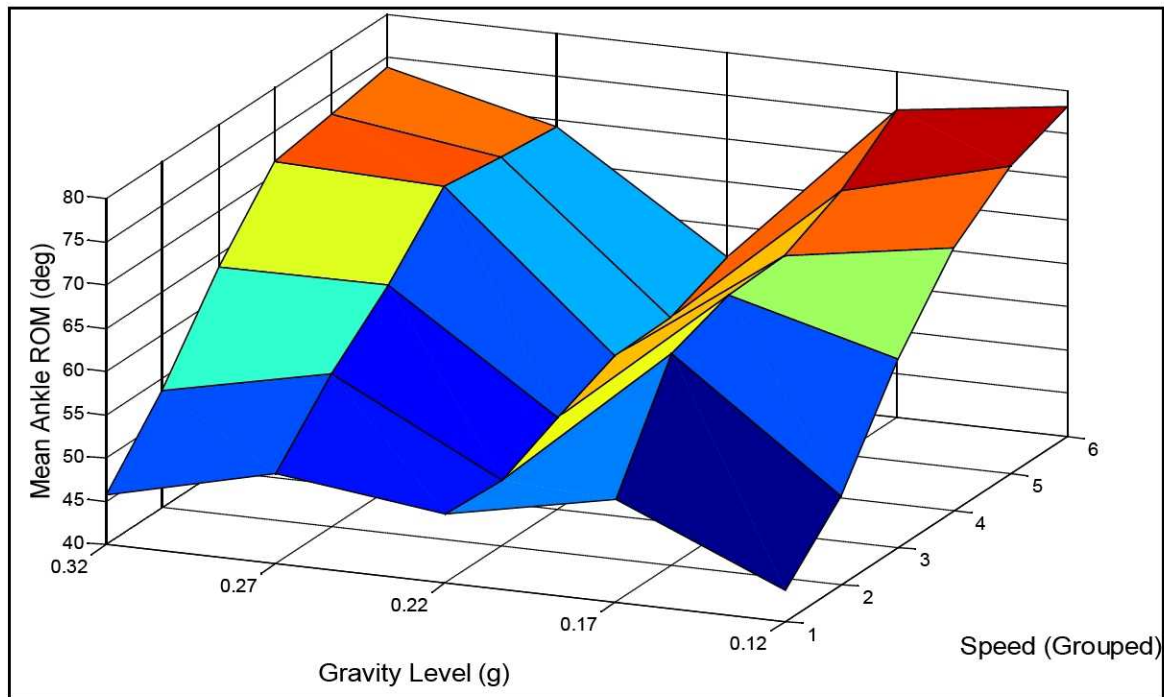


**Figure 32. Mean hip ROM during suited ambulation at different gravity levels and speeds. The parametric colored surfaces represent the ROM value. The color scheme of warm to cool colors indicates the magnitude of the ROM value. The warmer colors (yellows, oranges, and reds) are the extreme values observed. Conversely, the cooler colors (blues) demonstrate the lower values observed.**





**Figure 33.** Mean knee ROM during suited ambulation at different gravity levels and speeds. The parametric colored surfaces represent the ROM value. The color scheme of warm to cool colors indicates the magnitude of the ROM value. The warmer colors (yellows, oranges, and reds) are the extreme values observed. Conversely, the cooler colors (blues) demonstrate the lower values observed.



**Figure 34.** Mean ankle ROM during suited ambulation at different gravity levels and speeds. The parametric colored surfaces represent the ROM value. The color scheme of warm to cool colors indicates the magnitude of the ROM value. The warmer colors (yellows, oranges, and reds) are the extreme values observed. Conversely, the cooler colors (blues) demonstrate the lower values observed.

In summary, as weight increased there was a general increase in stance time, cadence, peak vertical ground reaction force. Joint ROM for the hip, knee, and ankle showed inconsistent trends and an anomalous finding at 0.22-g. Coupling these biomechanics changes with the metabolic data indicates that with increasing weight, there was likely an increase in mechanical work being done. This could be seen as advantageous as an exercise countermeasure, but disadvantageous as far as EVA consumables are concerned.

Another biomechanical parameter employed to examine the effects of offload was the Floquet multiplier, which is a tool that is commonly used to transform periodic cycles to a traditional linear system known as Floquet's theory. Simply, Floquet's theorem uses ordinary differential equations to convert a periodic function into a traditional linear function. The end results of Floquet's theorem are eigenvalues, ranging between 0 and 1, of the mathematical matrix that defines the linear system. In gait studies, this eigenvalue is often used as a measure of stability (13). Since there are many gait cycles during walking, the maximum eigenvalue is identified. The maximum eigenvalue is used as an overall stability measure, because it is the value that dominates the dynamic system. In other words, the closer the maximum eigenvalue is to the value of 1, the less stable the person is walking and the longer it takes the individual to return to steady state locomotion. If the maximum eigenvalue exceeds the value of 1, then the person has become so unstable that they have fallen or tripped. For purposes of gait analysis in this report, we use the term "Floquet multiplier" as a more specific name for the eigenvalue derived from the Floquet's analysis. The Floquet multiplier data did not demonstrate any observable trends across speeds or offload (Figure 35).

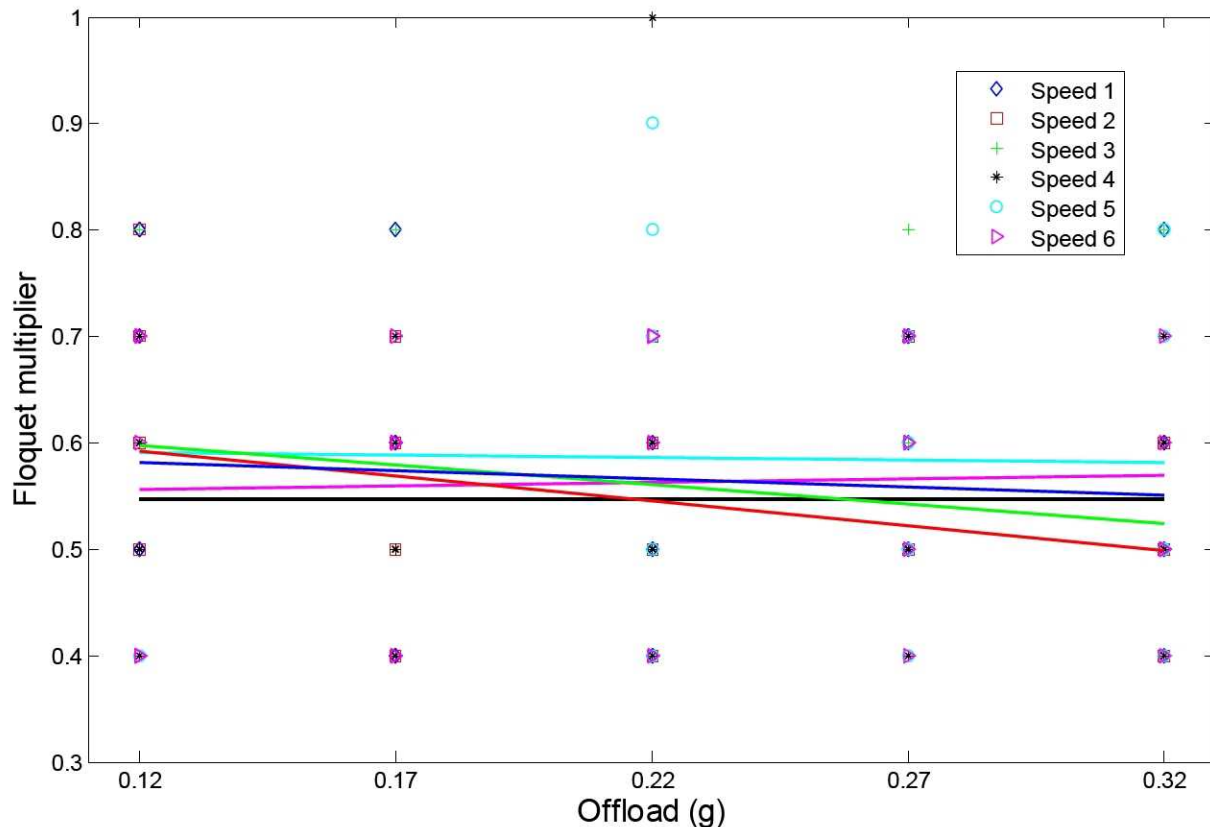


Figure 35. Floquet multiplier during suited ambulation at different gravity levels and speeds

### 3.2.3 Effect of Varied Mass

Initial findings showed no significant differences in metabolic rate as a function of added inertial mass to constant weight subjects (Figure 36).

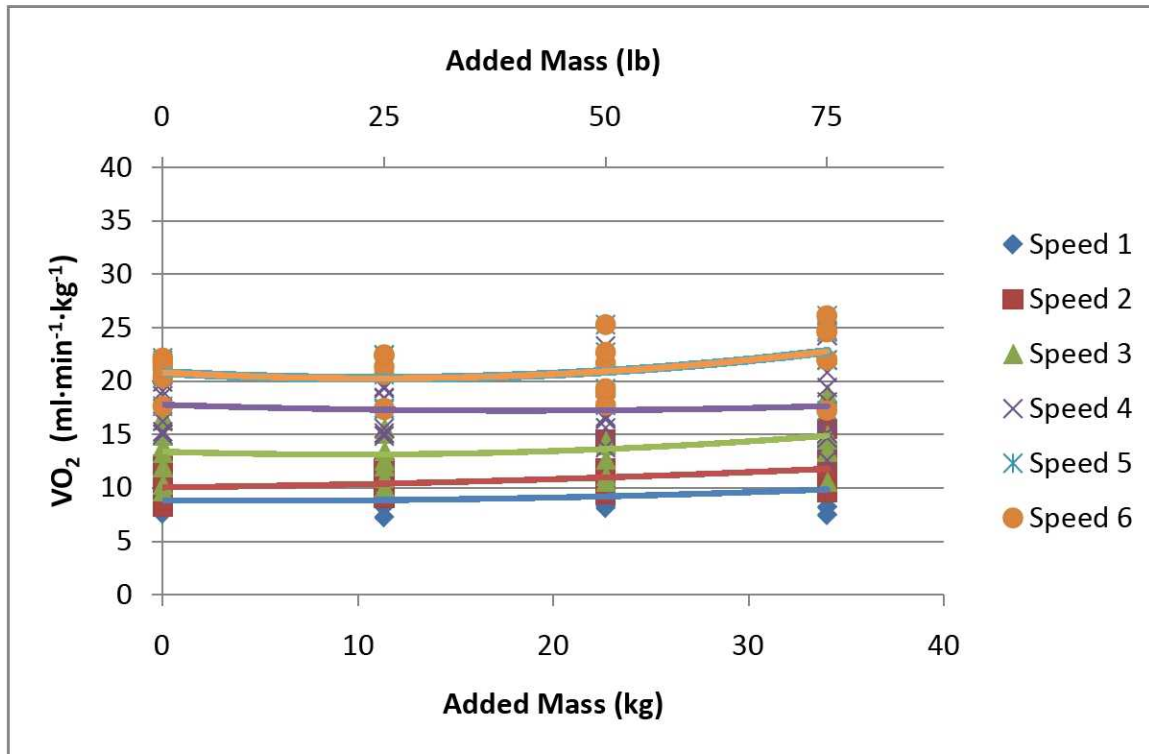


Figure 36. Metabolic rate versus added mass increments for unsuited locomotion while weight-matched to the 121 kg suit mass/weight at lunar gravity

One possible reason for this lack of variation is that the tension of the straps providing the overhead suspension were altered while wearing the vest and limited the subjects' range of motion. Another reason may be that the weight was not evenly distributed across the whole body, but limited to the torso. Finally, the increments tested may have been too small to see a realistic trend. The initial plan to use the unpressurized MKIII suit without a helmet to establish a 121 kg mass was not practical as increased joint wear was observed from ambulating in the unpressurized suit (see Appendix D for further details). Modifications to the gimbal support system to accommodate shirt sleeved and suited subjects along with the ability to add and remove mass to the system would provide a better platform to investigate the effects of inertial mass.

### 3.3 Test Objective 3: Compare MKIII at POGO Configuration to the MKIII at POGO Configuration with the Waist-Bearing Locked

To evaluate whether a waist joint may be necessary for ambulation in a space suit, the waist bearing was locked at the POGO configuration of 121 kg, 29.6 kPa (4.3 psi) and 1/6-g. This prevented rotation of the waist, but the convolutes still allowed flexion and extension. The metabolic data indicated that locking the MKIII waist bearing did not affect metabolic rate during level ground ambulation (Figure 37).



While the metabolic rate was not different between nominal and waist-locked conditions, the subjective ratings did differ. As shown in Figure 38 and Figure 39, the average RPE was slightly higher for the waist-locked condition versus nominal. The waist-locked condition was always performed last which could explain the increased exertion levels over the nominal conditions. The GCPS values for the waist-locked condition were higher than without the waist locked. However, the average GCPS ratings were below 4 for the waist-locked condition. Although GCPS ratings were higher in the waist-locked condition, there was no difference in metabolic rate. This indicates that while subjects felt it required more compensation to maintain performance, they were not expending any more energy to compensate.

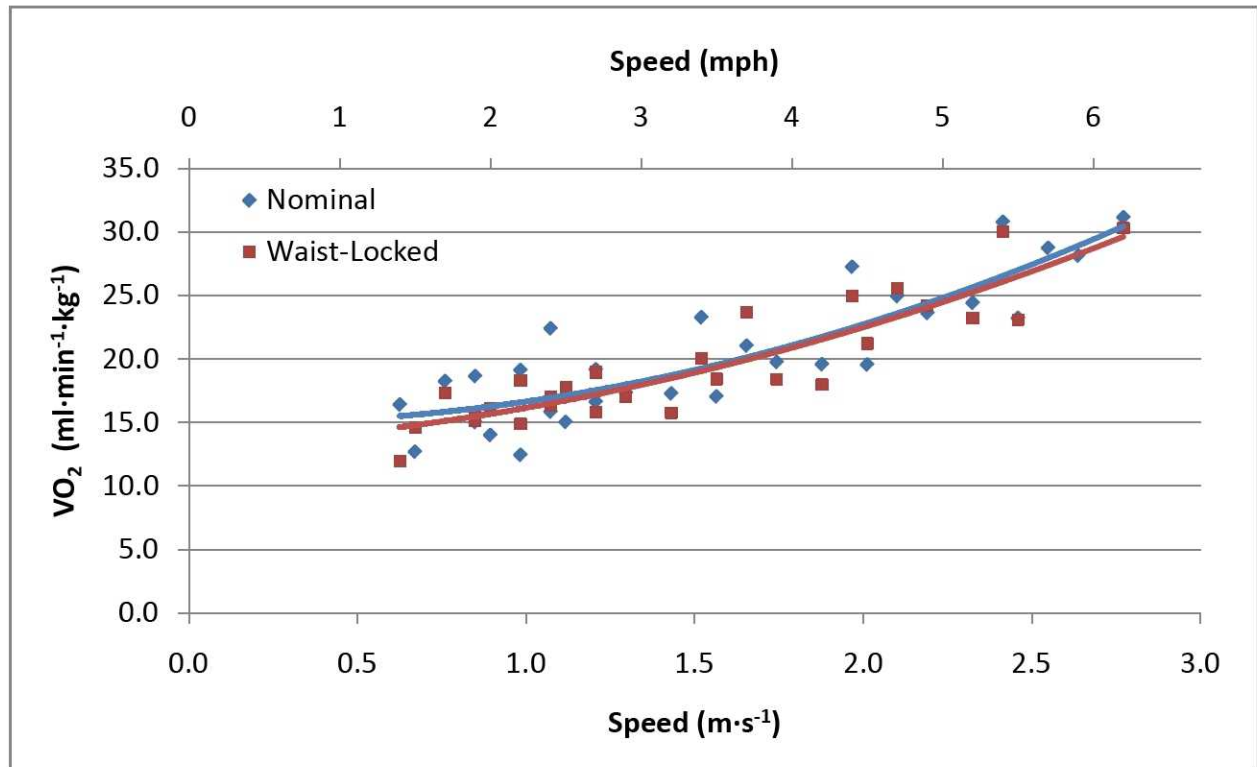


Figure 37. Metabolic rate with the MKIII waist bearing locked compared to nominal suit configuration during suited ambulation at lunar gravity with suit mass of 121 kg and suit pressure of 29.6 kPa



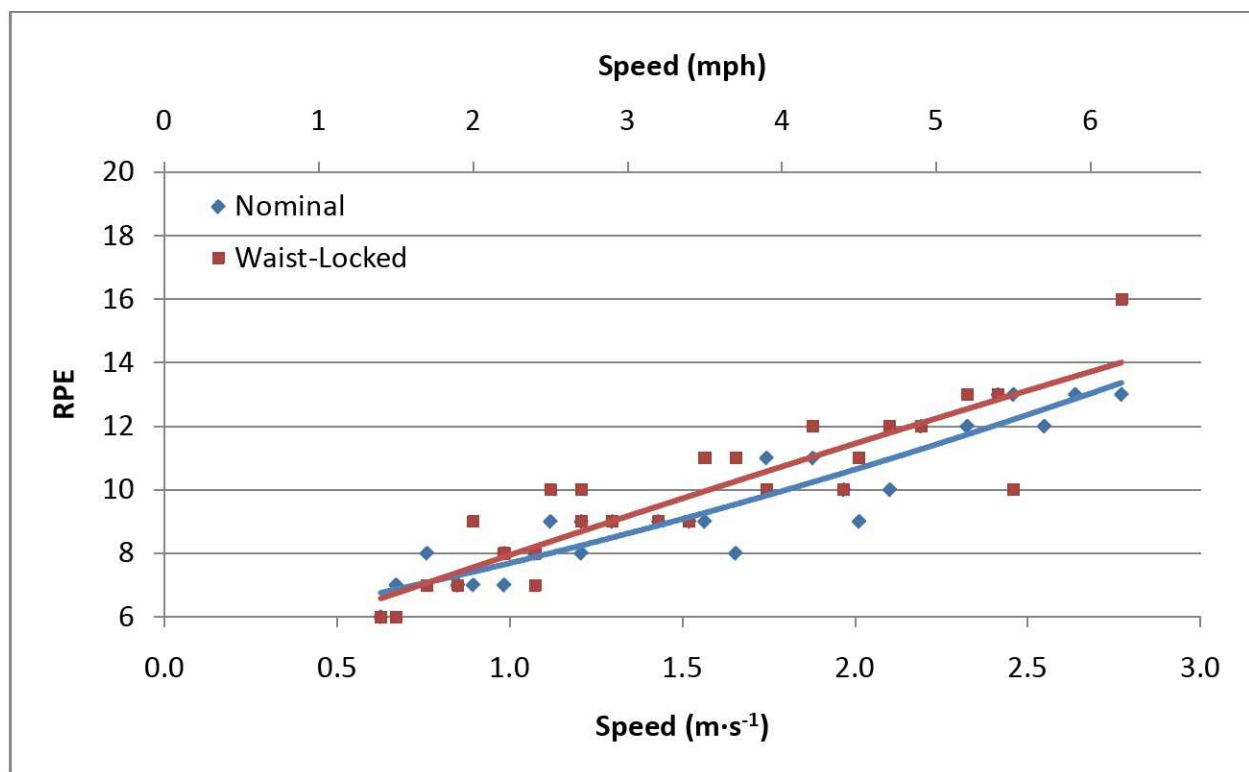


Figure 38. RPE with the MKIII waist bearing locked compared to nominal suit configuration during suited ambulation at lunar gravity with suit mass of 121 kg and suit pressure of 29.6 kPa

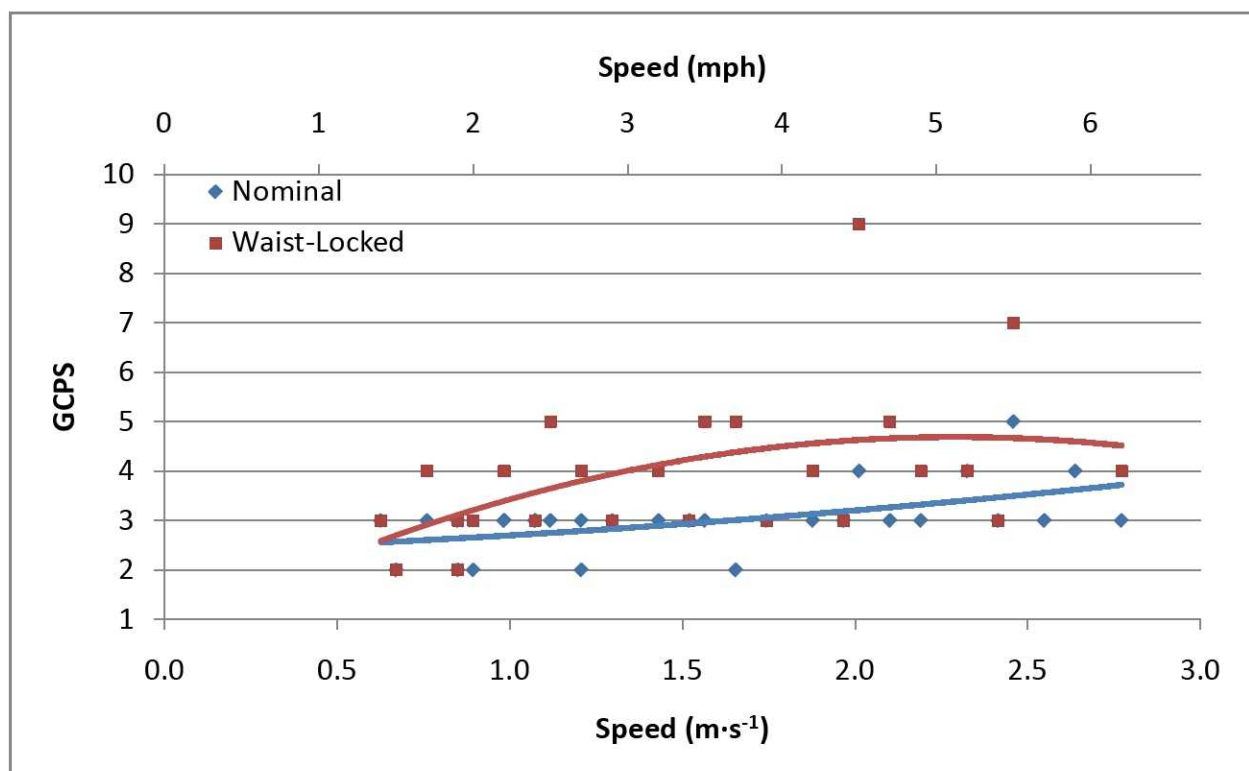


Figure 39. GCPS with the MKIII waist bearing locked compared to nominal suit configuration during suited ambulation at lunar gravity with suit mass of 121 kg and suit pressure of 29.6 kPa

The calculated hip and knee ROM percentage change between the waist locked and unlocked conditions are provided in Table 4 and Table 5 for 5 of the 6 subjects (one subject did not complete the task). There was no observable difference between the two conditions. This comparison was heavily dependent on the type of gait style chosen by the subjects. The type of gait style chosen by each subject is also roughly categorized and provided in Table 4 and Table 5.

**Table 4. Hip ROM percentage change between waist locked and unlocked conditions for speeds 3 through 6**

	Speed 3	Speed 4	Speed 5	Speed 6	Avg	Locked	Unlocked
<b>Subject B</b>	35	39	36		<b>37</b>	Hop	Bound
<b>Subject C</b>	-31	-14	4		<b>-14</b>	Hop	Hop
<b>Subject E</b>	-7	48	19	14	<b>19</b>	Hop/Bound	Hop/Bound
<b>Subject G</b>	-6	17	12	7	<b>8</b>	Hop/Bound	Bound
<b>Subject H</b>	-14	-4	-6	-17	<b>-10</b>	Run	Skip
<b>Average</b>	<b>-5</b>	<b>17</b>	<b>13</b>	<b>2</b>			

**Table 5. Knee ROM percentage change between waist locked and unlocked conditions for speeds 3 through 6**

	Speed 3	Speed 4	Speed 5	Speed 6	Avg	Locked	Unlocked
<b>Subject B</b>	-9	25	-5		<b>4</b>	Hop	Bound
<b>Subject C</b>	25	6	1		<b>11</b>	Hop	Hop
<b>Subject E</b>	32	19	10	0	<b>15</b>	Hop/Bound	Hop/Bound
<b>Subject G</b>	16	29	26	34	<b>26</b>	Hop/Bound	Bound
<b>Subject H</b>	16	17	13	1	<b>12</b>	Run	Skip
<b>Average</b>	<b>16</b>	<b>20</b>	<b>8</b>	<b>17</b>			

### 3.4 Test Objective 4: Predictive Models of Metabolic Rates, Subjective Assessments, and Suit Kinematics

Test Objective 4 was “to develop predictive models of metabolic rates, subjective assessments, and suit kinematics based on measurable suit, task, and subject parameters”. Development of these models will eventually provide the NASA community with an easy to use tool that highlights the performance changes associated with manipulation of the suit, subject, and EVA characteristics. These models also could be used to prospectively predict results for future tests to validate or further refine the model against those results. It is our goal that the results of this test series can be refined into a validated model accessible to all within the EVA science, engineering, and operations community.

### 3.4.1 Predictive Model for Metabolic Rate #1

A preliminary multiple linear regression model was developed to predict the metabolic rate of locomotion in the MKIII suit as a function of the properties of the suit, the anthropometry of the subject and the speed of locomotion. The model was developed as an example of the type of predictive model that will be developed and refined in greater detail as additional integrated suit test data are collected and analyzed. Inferential statistics were not calculated because of the small sample size ( $n = 6$ ).

The input variables were the subject weight and leg length, total gravity adjusted weight, suit pressure, and the ambulation speed. The preliminary model used the following combination of variables to predict normalized metabolic rates during locomotion in the MKIII EVA suit:

**Equation 1. Model for predicting metabolic rate based on suit, task and subject parameters**

$$MR = b_0 + b_1 \cdot (V_{\text{locomotion}} \times W_{\text{total}}) + b_2 \cdot M_{\text{body}} + b_3 \cdot (W_{\text{total}} \times L_{\text{leg}}) + b_4 \cdot P_{\text{suit}}$$

where

MR	= metabolic rate expressed as normalized $\text{VO}_2$ ( $\text{mL} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$ )
$V_{\text{locomotion}}$	= locomotion speed ( $\text{m} \cdot \text{s}^{-1}$ )
$W_{\text{total}}$	= total gravity adjusted weight of EVA suit plus astronaut (N)
$M_{\text{body}}$	= body mass of unsuited astronaut (kg)
$L_{\text{leg}}$	= leg length of astronaut (cm)
$P_{\text{suit}}$	= suit pressure (kPa)

The method of least squares was used to estimate the parameters ( $b_0 - b_4$ ) from the experiment data. Predictor variables used in the model were chosen a) to produce as good a fit as possible with a minimum number of terms and b) to contain reasonable explanatory information. The proportion of variance explained by the preliminary model ( $R^2$ ) was 0.846 and the root mean square error was  $2.52 \text{ mL} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$ , which is less than the  $3.5 \text{ mL} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$ , which was deemed to be of practical significance.

Cross-validation was performed by estimating model parameters from experimental data from half the subjects (subset 1) and using those parameters to predict the experimental observations recorded for the remaining subjects (subset 2). This process was then repeated by estimating model parameters using subset 2 data and using those parameters to predict subset 1 observations. Thus, the model parameters were estimated using three different data sets: using all data, using subset-1 data, and using subset-2 data. In all three cases, the signs of the model parameters were consistent, the proportion of explained variance correlation coefficient ( $R^2$ ) was 0.831 or greater, and the root mean square error did not exceed  $2.61 \text{ mL} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$  when each subset model predicted metabolic rates for the other half of the data.

The large proportion of explained variance ( $R^2$ ) and the small root mean square error combined with the results of the cross-validation analysis indicate that this preliminary model provides good prediction of normalized metabolic rates for this data set. However, this model should not be generalized beyond the conditions under which the data was collected. Descriptive statistics for the six astronaut subjects are shown in Table 1. The range of experimental conditions is shown in Table

3. Further data collection planned in forthcoming suit test protocols combined with detailed characterization of subject anthropometry, strength and fitness will enable development of the model such that it may be generalized to a larger range of EVA tasks, suit configurations, and astronaut population.

**Table 6. Range of experimental conditions upon which preliminary model is based**

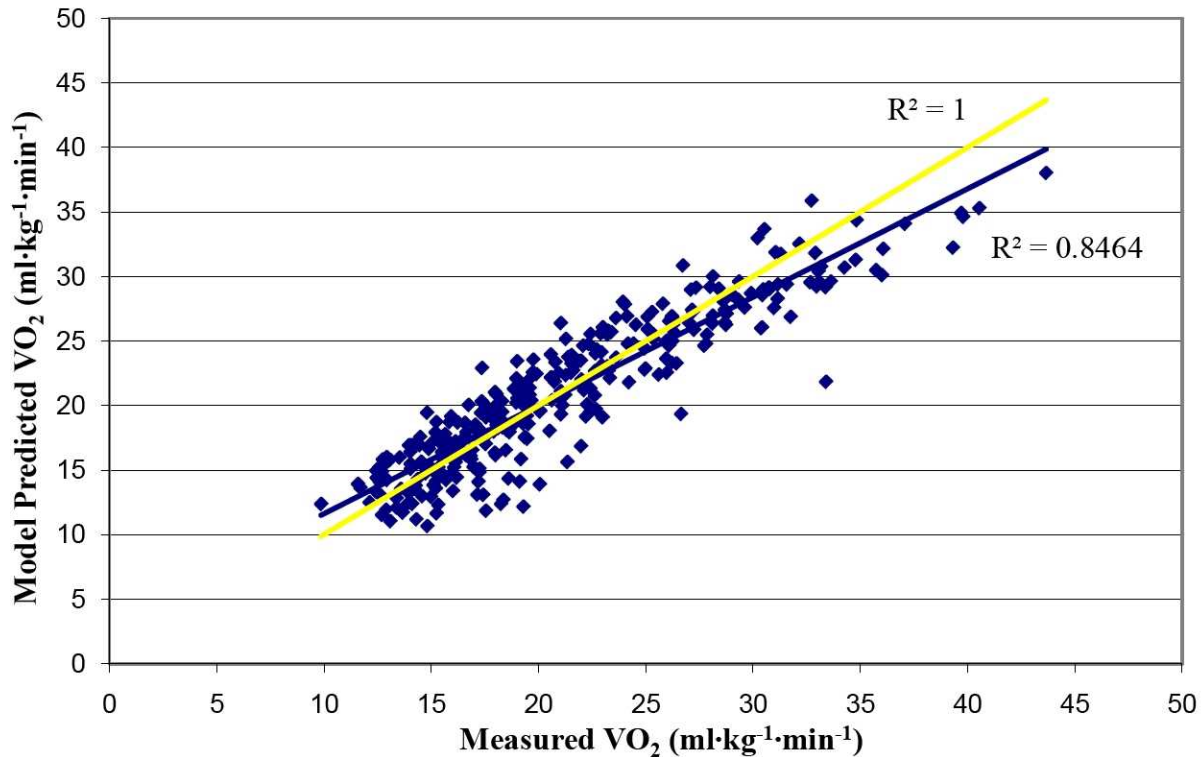
Gravity Level	Total Gravity Adjusted Weight	$P_{\text{suit}}$				
		6.9 kPa (1.0 psi)	20.7 kPa (3.0 psi)	29.6 kPa (4.3 psi)	34.5 kPa (5.0 psi)	44.8 kPa (6.5 psi)
0.12-g	222–245 N (50–55 lb)			0.64–2.78 $\text{m}\cdot\text{s}^{-1}$		
0.17-g	307–343 N (69–77 lb)	0.64–2.78 $\text{m}\cdot\text{s}^{-1}$	0.64–2.78 $\text{m}\cdot\text{s}^{-1}$	0.64–2.78 $\text{m}\cdot\text{s}^{-1}$	0.64–2.78 $\text{m}\cdot\text{s}^{-1}$	0.64–2.78 $\text{m}\cdot\text{s}^{-1}$
0.22-g	405–449 N (91–101 lb)			0.64–2.78 $\text{m}\cdot\text{s}^{-1}$		
0.27-g	498–552 N (112–124 lb)			0.64–2.33 $\text{m}\cdot\text{s}^{-1}$		
0.32-g	592–654 N (133–147 lb)			0.64–2.33 $\text{m}\cdot\text{s}^{-1}$		

The application of this model is currently limited to level ground ambulation with the subjects and conditions described in Table 1 and Table 6. Currently, this model is a statistically descriptive fit for the IST-1 data, but we plan develop a more generalized predictive model for metabolic cost, whose parameters can be optimized from a range of suit test data Further expansion of this model will include incline walking and various exploration tasks as these activities have different subject-suit interactions.

Given the limitations of this current model, it is still important to demonstrate the utility of a predictive model of metabolic rate as it relates to determining suit and EVA consumable requirements.

We've previously described  $3.5 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$  as the level of significance when dealing with metabolic rate. Using the model to predict metabolic rate, this cut-off point for significance is greater than the root mean square error of  $2.52 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ . Figure 40 demonstrates the predictive accuracy of this descriptive model by showing the majority of predictions are clustered tightly around measured  $\text{VO}_2$ . Further review indicates that the majority of predicted values are within  $3.5 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$  of measured  $\text{VO}_2$  independent of speed.





**Figure 40. Difference between model predicted and measured  $\text{VO}_2$  versus speed for all suited data collection points**

Preliminary application of this model would encompass locomotion only. Recommendations for suit pressure would assume a 121 kg suit/system mass and recommendations for suit mass will assume a 29.6 kPa (4.3 psi) suit pressure and currently relies on the assumption that a change in weight (TGAW) reasonably represents a change in suit mass. Application of the model requires a set of assumptions for the speeds expected during locomotion. Digital video analysis from the Apollo films, as well as inputs from the Lunar Architecture Team and results of the EVA Walkback Test, provides the following set of assumptions regarding operational concepts for lunar exploration:

- $0.4$  to  $0.8 \text{ m}\cdot\text{s}^{-1}$  ( $\sim 1.0$  to  $2.0$  mph) is the range assumed for intrasite translations for various contextual observations and EVA tasks
- $1.1$  to  $1.4 \text{ m}\cdot\text{s}^{-1}$  ( $\sim 2.5$  to  $3.0$  mph) is the range of ambulation speeds for site to site translations defined as direction translation between points of interest (this speed range may be less important if crewmembers use a rover for the majority of site to site translations)
- $1.8 \text{ m}\cdot\text{s}^{-1}$  ( $\sim 4$  mph) is assumed as the optimal speed for a 10 km walkback contingency (1) (with an operational concept employing dual rovers, then walkback contingency would not be required in response to a failed rover, however, high speed translations might be required for short distances to return to the life support on the rover in response to various suit malfunctions).

This predictive model of metabolic rate can be used as a tool to understand how suit weight and/or pressure affects the overall metabolic cost and thus consumables usage under different operational concepts. The predictive model suggests that suit pressure from 6.9 to 44.8 kPa at a suit mass of 121 kg did not significantly change metabolic rate across the range of ambulation speeds from intrasite

translations to contingency walkback. The predictive model for EVA shows significant differences in metabolic rate depending on suit weight and ambulation speeds. Figure 41 demonstrates how varying the mass of the suit up or down from the baseline 121 kg configuration at 29.6 kPa (4.3 psi) changes the metabolic rate as a function of speed within various operational ranges for level ground ambulation. At this time the model is limited to level ground ambulation in the MKIII suit and relies on the assumption that a change in weight as was tested during IST-1 reasonably represents a change in suit mass. Future studies would need to determine if a change in weight reasonably represents the true change in metabolic rate that would be seen with that same change in suit mass. In the future, models will expand to include ambulation as a function of inclination angle and performance of various exploration tasks.

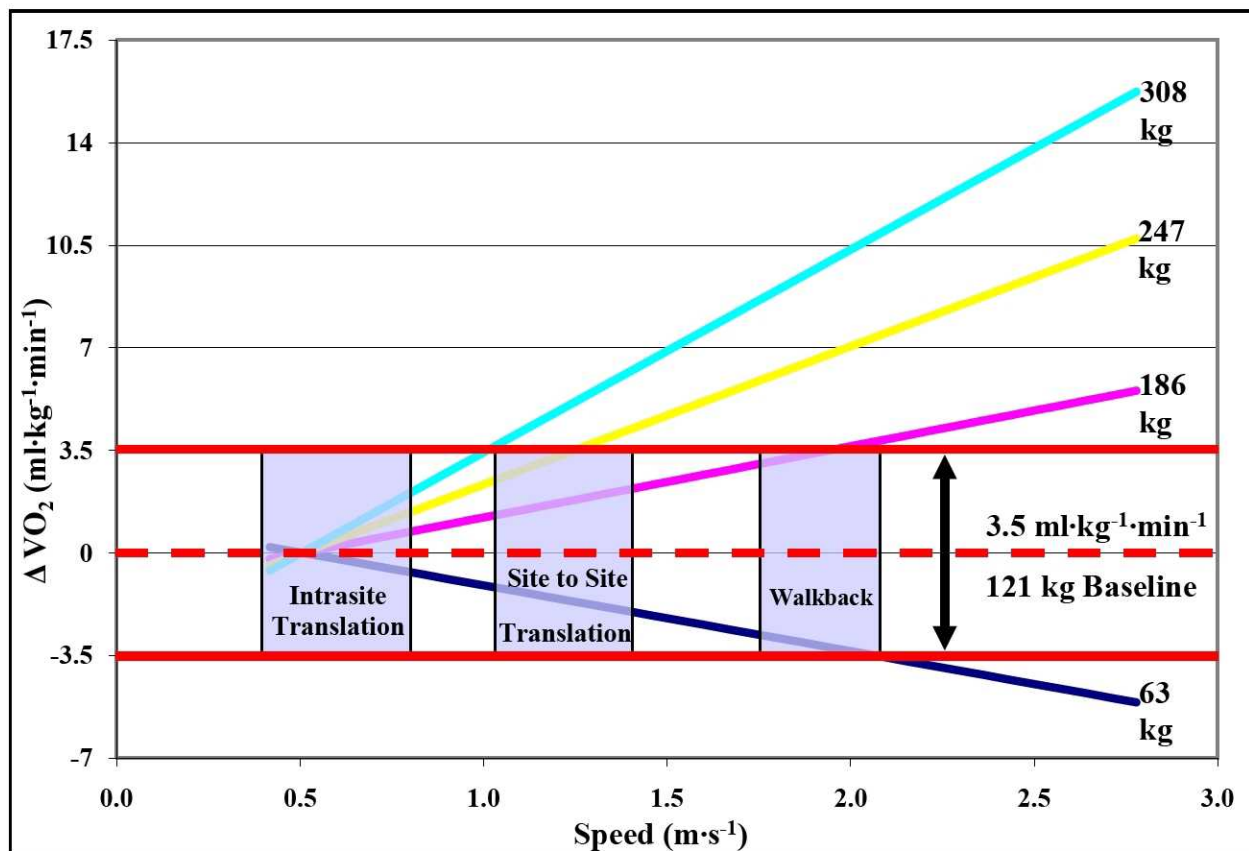


Figure 41. Modeled data showing theoretical  $\Delta VO_2$  at 29.6 kPa as suit mass varies from 121 kg across different operational speeds

Figure 41 suggests that for intrasite translations, there would not be a significant difference between any of the suit masses. For site to site translations, suit masses between 63 to 186 kg would not be significantly different; the 308 kg suit would be significantly higher than the baseline configuration for the full range of site to site translations speeds, while the 247 kg suit would be significantly higher for the upper range of speeds. For the walkback contingency, there would be significant differences between the baseline configuration and all other suit masses with the 63 and 186 kg suits just beginning to be significantly different in the positive and negative directions respectively. Preliminary and unverified application of this model might indicate that although weight significantly affects metabolic cost, a larger than expected range of suit masses from 63 to 186 kg might be acceptable for various operational translation speed ranges.

### 3.4.2 Predictive Model for Metabolic Rate #2

For this study, we focus on predicting  $\text{VO}_2$  from subject's GCPS, RPE and whether or not they were suited for the task (Suit). Mixed-effect regression analysis was used to model  $\text{VO}_2$  from RPE, Suit, and GCPS scores, including subject-level grouping to accommodate for the dependence in the data (i.e., repeated observations within subjects), and a random intercept term to allow subjects to vary randomly on the y-intercept of the model. Log transformations of the  $\text{VO}_2$  outcome before predictive modeling was done to improve the non-normal distribution of the data, as well the residuals from our statistical model. The model residuals appeared normally distributed with constant variance over the range of the outcome, suggesting that the transformed data are appropriately analyzed with these techniques.

The model revealed that 2 of 3 predictors made significant variance contributions to  $\text{VO}_2$  in this multivariate context ( $P < .05$ ), with the highest relative contribution observed for the RPE predictor. In this data set, GCPS was not a statistically significant component of the model, but was included because it increased the overall predictive accuracy of the model and had been a significant component in a similar model constructed with the EWT dataset. RPE scores were positively correlated with  $\text{VO}_2$ , suited  $\text{VO}_2$  levels were higher than unsuited, but GCPS scores were negatively associated with  $\text{VO}_2$  in this model. Model predicted and observed  $\text{VO}_2$  values are shown in Figure 42. Variation in  $\text{VO}_2$  seen per unit of RPE is not fully characterized by the model, but rather model predicted values cluster around the mean.

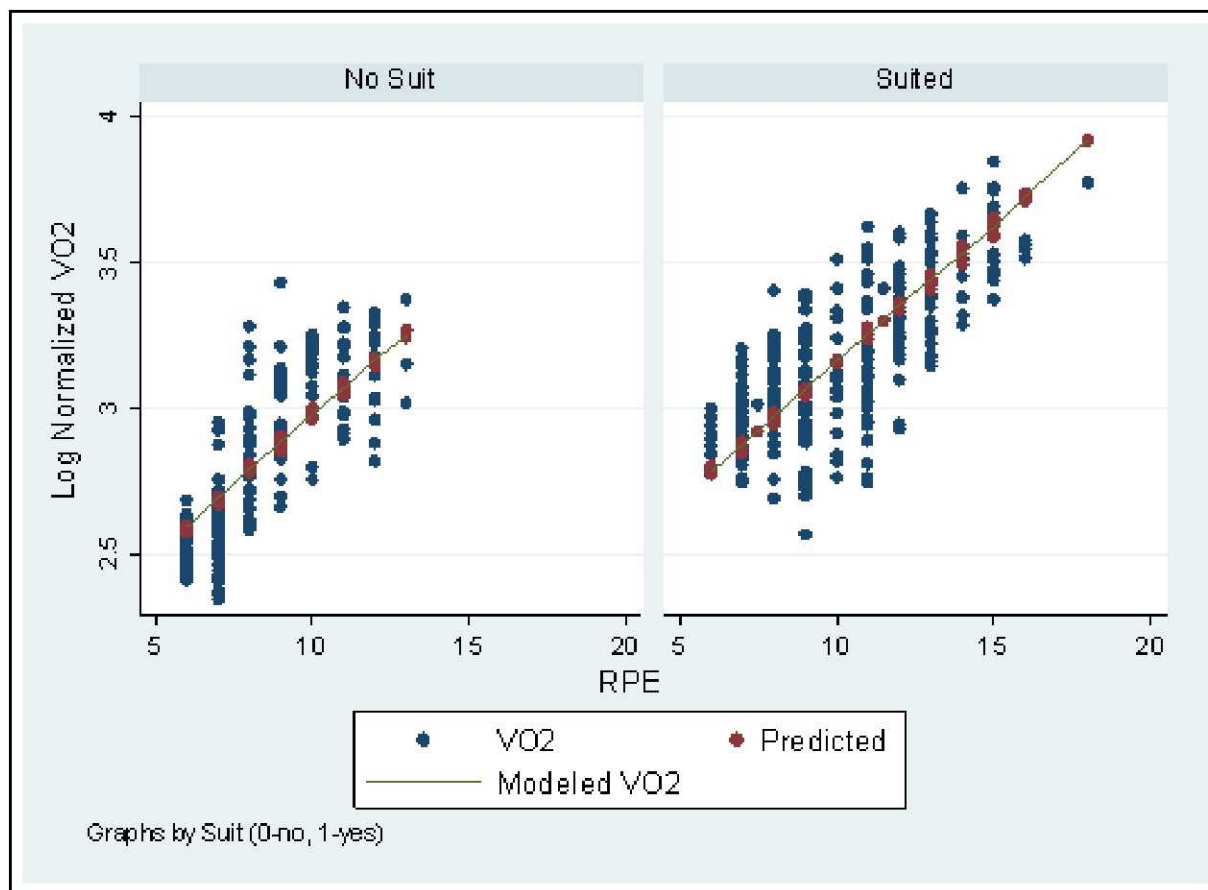


Figure 42. Model predicted  $\text{VO}_2$  (red) and observed  $\text{VO}_2$  (blue) with respect to RPE



While these effects are statistically significant to traditionally held scientific standards, the reader is reminded that they are based on a very small sample of  $n = 6$  astronauts. We remain cautious about making inferences to the larger astronaut population or outside of level ground ambulation until these results can be replicated in future work.

### 3.4.3 Predictive Model for Subjective Ratings

Using the same methods as described for the metabolic rate model, a predictive model for RPE was also created. Using ordered logistical regression, a model to predict the probability of a certain GCPS range was also created. As described previously, these are preliminary descriptive models that currently only apply to level ground ambulation in the MKIII suit within the given parameters described in Table 1 and Table 6. Once equipped with more information, advanced application of these models may help understand the human factors of future EVA suits.

The preliminary models for RPE and GCPS used the same combination of independent variables as described in Equation 1, except that MR was replaced with RPE or GCPS as the dependent variable.

The method of least squares was used to estimate the parameters ( $b_0 - b_4$ ) from the experiment data. Predictor variables used in the model were chosen a) to produce as good a fit as possible with a minimum number of terms and b) to contain reasonable biomechanical explanatory information. The parameter estimates are shown in Table 3. The  $R^2$  for the RPE model was 0.804 and the root mean square error was 1.17. Figure 43 demonstrates the predictive accuracy for this model given the assumption that an  $RPE \pm 1$  is not noticeable to a subject. This assumption falls just under the root-mean squared error of the model.

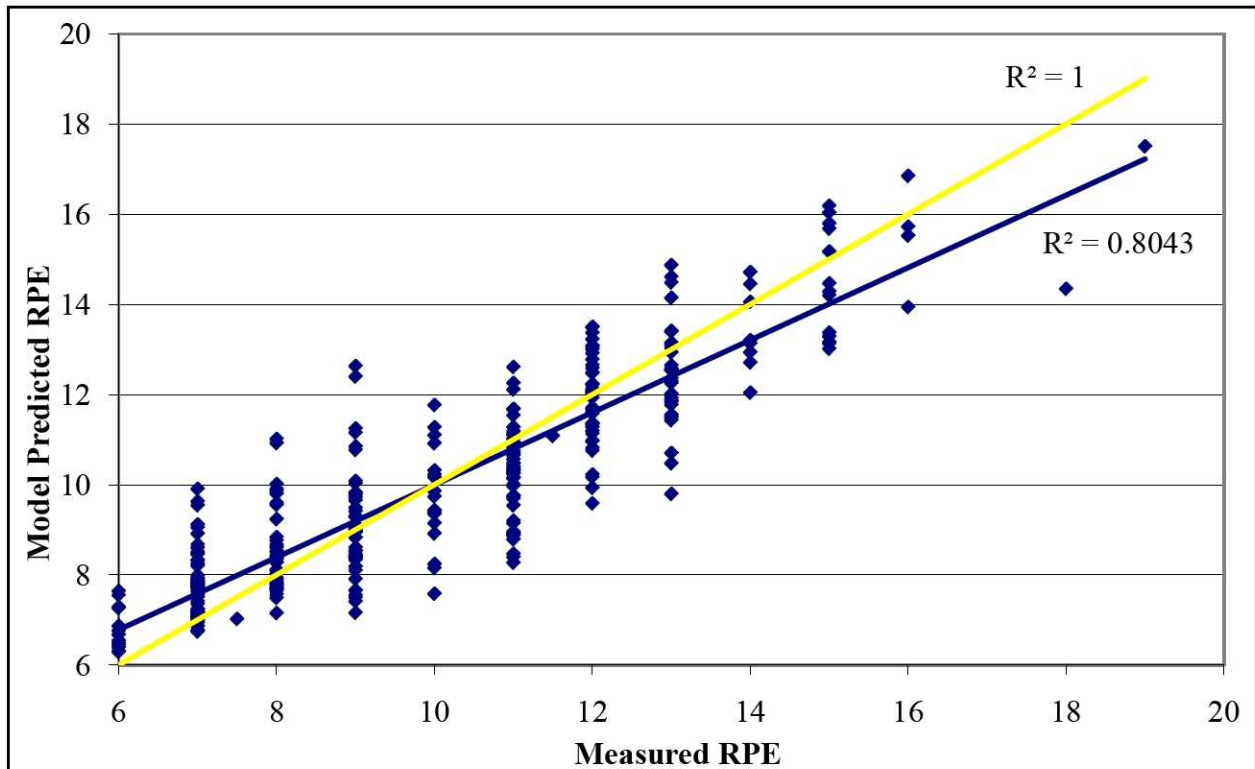


Figure 43. Difference between model predicted and measured RPE versus speed for all suited data collection points



Because the GCPS scale is not a continuous function, an ordered logistical regression model was selected to determine the probability of a given value given a set of inputs. For this type of model, the GCPS scale was broken down into 3 distinct categories. GCPS ratings of 1 to 3 were deemed “acceptable”, ratings of 4 to 6 were deemed “modifications warranted” and ratings  $\geq 7$  were deemed “modifications required”.

For example, consider an average male crewmember of 82 kg and 105-cm leg length in the reference configuration of the MKIII suit (121 kg and 29.6 kPa). Table 7 describes how speed affects the probability of GCPS ratings while keeping the subject, suit mass, and suit pressure constant.

**Table 7. Probability of a given GCPS rating as a function of speed (Assuming: 82 kg subject, 105 cm leg length, 121 kg suit/system mass, 29.6 kPa suit pressure)**

Level Ambulation Speed	GCPS Probability		
	Acceptable	Modifications Warranted	Modifications Required
0.75 m•s <sup>-1</sup> (1.7 mph)	91%	9%	0%
1.25 m•s <sup>-1</sup> (2.8 mph)	80%	20%	0%
1.75 m•s <sup>-1</sup> (3.9 mph)	61%	38%	1%
2.25 m•s <sup>-1</sup> (5.0 mph)	29%	69%	2%

Now assume a 1.25 m•s<sup>-1</sup> translation speed, we can take the same male crewmember (82 kg, 105 cm leg length) and maintain a constant pressure (29.6 kPa) but vary the suit mass. Table 8 describes the affect of varying the suit weight on GCPS ratings.

**Table 8. Probability of a given GCPS rating as a function of suit mass (Assuming: 82 kg subject, 105 cm leg length, 29.6 kPa suit pressure, 1.25 m•s<sup>-1</sup> speed)**

Suit Mass (kg)	GCPS Probability		
	Acceptable	Modifications Warranted	Modifications Required
63	87%	13%	0%
121	80%	20%	0%
186	69%	31%	0%
247	57%	43%	1%
308	43%	55%	1%

Because GCPS ratings were primarily in the acceptable or modifications warranted ranges for IST-1, “modifications required” ratings will usually have a low probability based on this model. Future studies will provide additional data and more insight into all three ranges.

### 3.4.4 Predictive Model for Suit Kinematics

Predictive models also will be developed to predict the number of joint cycles and/or joint displacement across the ankle, knee, hip, and waist in the MKIII suit as a function of the properties of the suit, the anthropometry of the subject, and the speed of locomotion. These models will be developed as an example of the type of predictive model that can be developed and refined in greater detail as additional data is collected and analyzed to determine the number of cycles on any joint of the suit. These analysis tools will be effective for developing suit cycle requirements and will

provide significant cost savings during suit certification compared to the conventional methods of manual video tape review.

### 3.5 Secondary Test Objectives

#### 3.5.1 Define Standard Measures and Protocols for Evaluating Exploration Suits and Requirements Verification

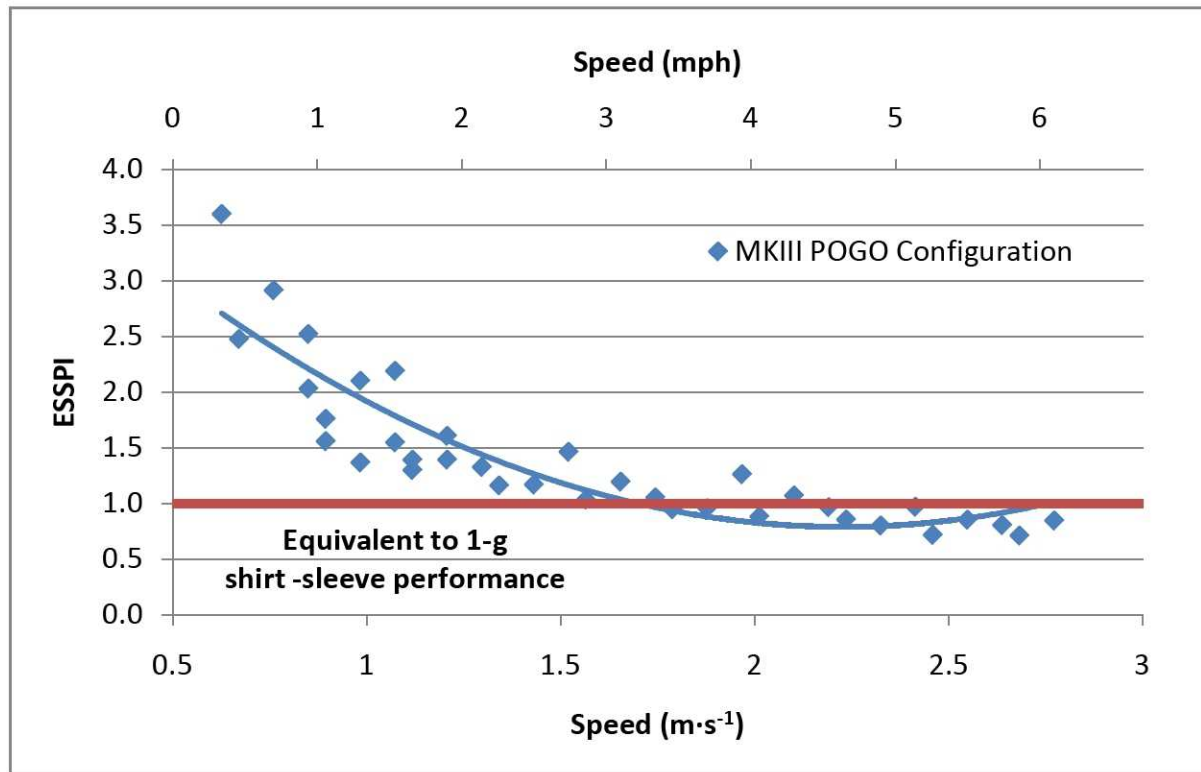
The protocols, instrumentation, and analysis techniques developed and applied for this test will be available for future testing of prototype exploration suits. The body of knowledge for how to conduct both suited and unsuited testing on the POGO has been greatly expanded. Techniques never before used in biomechanical analysis are being applied to suited models. By refining data collection techniques and developing an understanding of which factors affect human performance in the suit and in reduced gravity, we will be able to combine these objective measurements with crew subjective comments to assess the performance of future exploration suits.

#### 3.5.2 Understand the Specific Human Performance Limitations of a Suit Compared to Matched Shirt-Sleeve Controls

This is a complex problem involving comparison of suited human performance in reduced gravity to unsuited human performance in both reduced gravity and Earth gravity. Comparisons of suited to unsuited metabolic rate, while doing the same tasks in lunar gravity, provide the basis for the estimate of the metabolic cost of the suit. Although the systems in place for IST-1 allowed us to get preliminary data on this, the suspension methods of suited and unsuited subjects are quite different. Metabolic cost of the suit results as shown are preliminary and would benefit by having an improved gimbal support system that suspended suited and unsuited subjects in the same way.

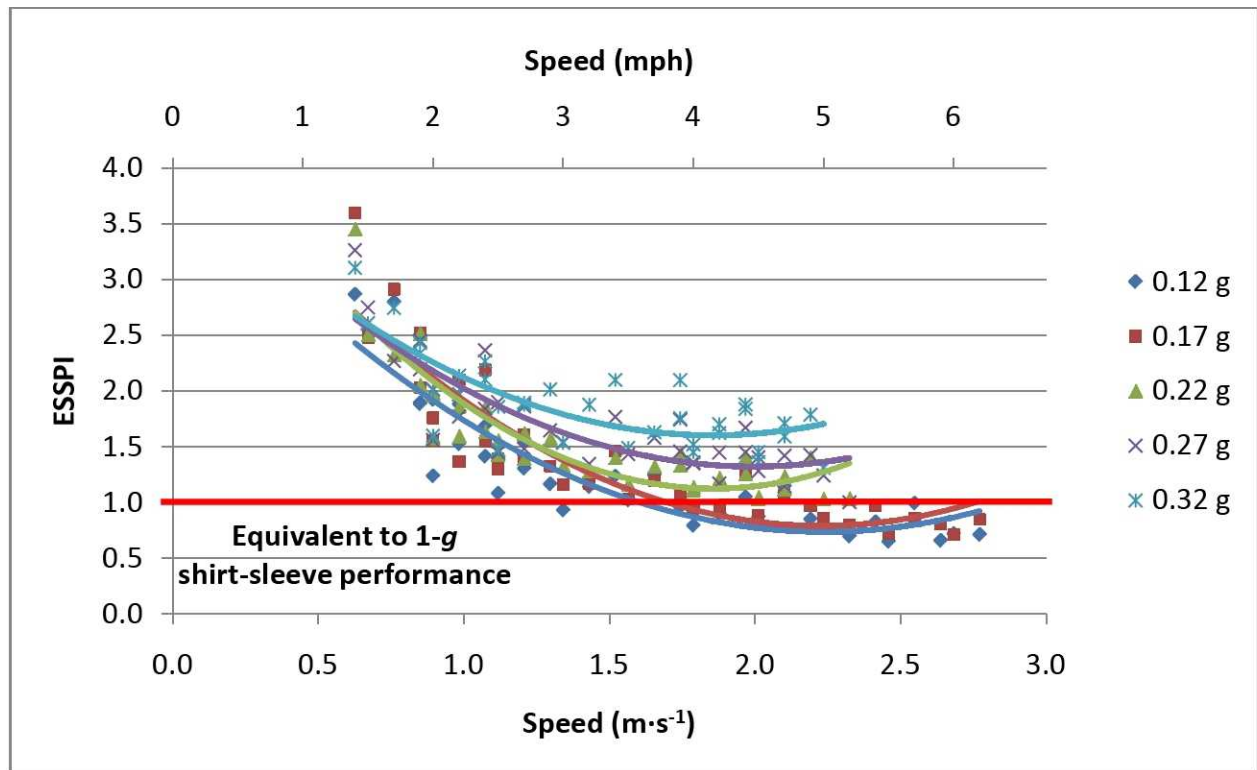
Metrics for comparing suited reduced gravity performance to Earth shirt-sleeve performance include the ESSPI and GCPS. The assumption behind both of these metrics is that Earth shirt-sleeve performance is the target for ideal suited human performance in reduced gravity. GCPS was previously described in the subjective findings relevant to Sections 3.2-3.4.

Figure 44 demonstrates the Earth Shirt-Sleeve Performance Index (ESSPI, defined in Section 2.4.3) as it relates to suited ambulation at lunar gravity with the MKIII in POGO configuration of 121 kg and 29.6 kPa (4.3 psi). At slow walking speeds, the metabolic cost of lunar ambulation was approximately 1.5 to 3 times that of Earth shirt-sleeved ambulation, whereas at speeds above  $1.75 \text{ m}\cdot\text{s}^{-1}$ , the metabolic cost of lunar running was lower than Earth shirt-sleeved conditions. This suggests that efforts to improve human performance while suited in 1/6-g need to be focused on the slower ambulation speeds, because performance at the faster speeds was already equivalent to 1-g shirt-sleeve performance, which is considered the ideal target.



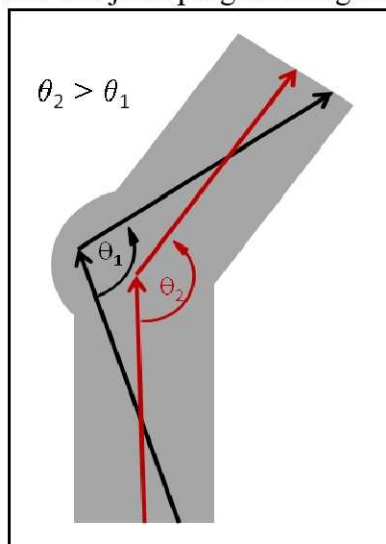
**Figure 44. ESSPI for suited ambulation at lunar gravity with a 121 kg suit weight at 29.6 kPa**

Figure 45 shows the ESSPI as a function of gravity level. Equivalent performance to 1-g shirt sleeve was only present at the two lowest gravity levels and at speeds greater than  $1.5 \text{ m}\cdot\text{s}^{-1}$ . Current operational concepts indicate that most ambulation will be at slower speeds ( $<1.5 \text{ m}\cdot\text{s}^{-1}$ ) and often times less than  $1.0 \text{ m}\cdot\text{s}^{-1}$ . Across all speeds, as weight increased, it was more difficult to achieve close to 1-g performance. While this may indicate that for ambulation purposes, a lighter suit leading to a lower TGAW would bring performance closer to 1-g shirt-sleeve performance it seems to make very little difference at the slower speeds.



**Figure 45. ESSPI versus speed at different gravity levels during suited locomotion at a constant mass (121 kg) and pressure (29.6 kPa)**

Finally, an understanding of how a subject moves differently in and outside of a suit is an important and yet quite difficult question to answer. One of the difficulties with this analysis is that the subject has a fair amount of travel within the suit before the suit actually moves. Some of the difficulties with quantifying the kinematic constraints that the suit imposes on human movement include differences between the human kinematics and the suit kinematics because of free space within the suit (see Figure 46), differences between the suit joints/break points and the human joint locations, and suit joint programming doesn't necessarily mimic human joint movement.



**Figure 46. Example of the current difficulties with studying how the suit affects human movement (a possible suit knee angle is shown in red and a possible human knee angle in black)**



### 3.5.3 Collect Metabolic and GRF Force Data to Develop an EVA Simulator for Use on Future Prebreathe Protocol Verification Tests

Data from this study and other studies of EVA and human performance in reduced gravity will be used in the development of an EVA simulator for use in the verification of prebreathe protocols. Four factors primarily affect the risk of decompression sickness: environmental pressure, time at reduced pressure, prebreathe time, and level of activity (14). Preliminary evidence suggests that a defined level of activity using  $\text{VO}_2$  may be more significant than previously thought (15), thus having an accurate and realistic simulation of EVA activities will help verify current and new prebreathe protocols. In addition to metabolic rate, GRF is also considered to be an important factor that an EVA simulator should to control for (16).

### 3.5.4 Provide Data to Estimate Consumables Usage for Input to Suit and PLSS Design

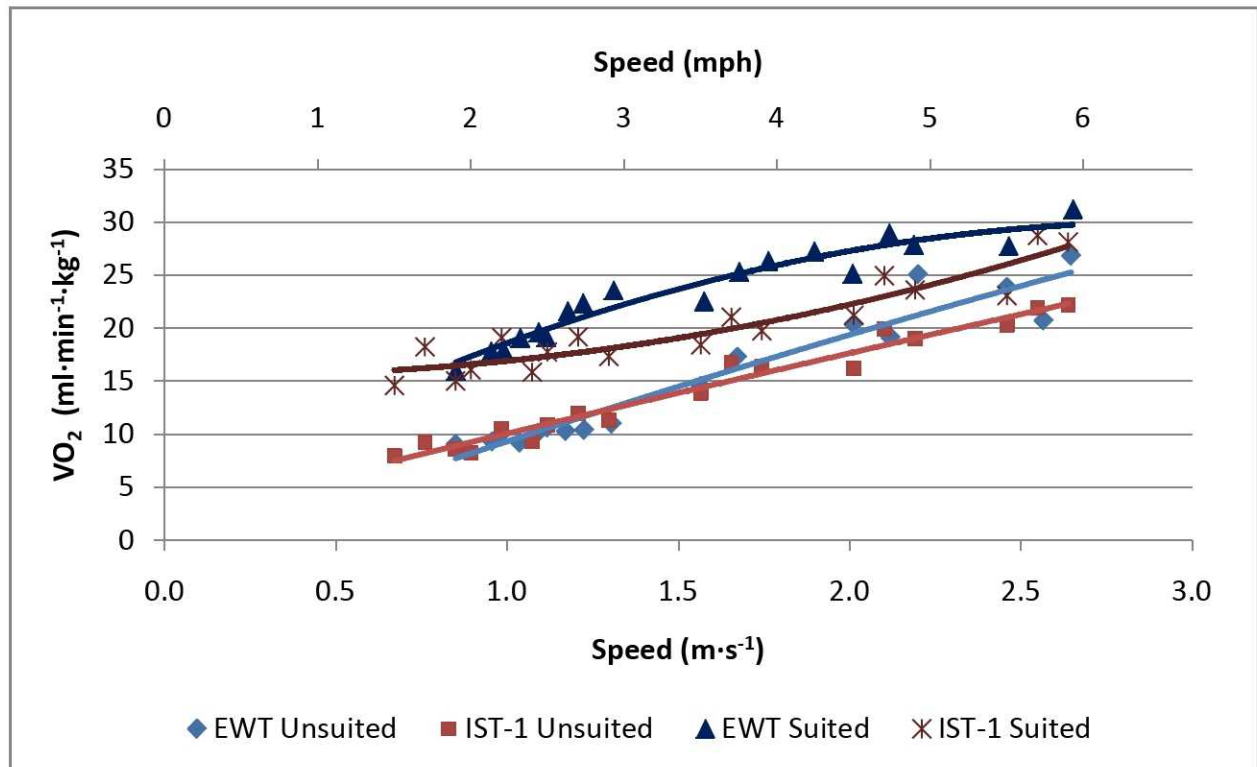
These data will be provided to the suit and PLSS team through the development of a comprehensive model that would provide the ability to alter crew, suit, and EVA activity parameters to see what effect this would have on consumable usage, joint displacement and crewmember subjective ratings. Eventual development of these models depends on increasing the amount of data by testing more tasks, more subjects, different suits, and in different lunar analog environments. Intermediate steps before the complete development of this model include providing inputs based on the data collected to date through test reports and data summary presentations.

### 3.5.5 Assess the Cardiovascular and Resistance Exercise Associated with Partial Gravity EVA for Planning Appropriate Exploration Exercise Countermeasures

To what extent lunar gravity and lunar EVA will provide a countermeasure to the deconditioning of crewmember's muscular, cardiovascular, and bone systems is poorly understood. Much has been learned through previous microgravity research on the development of effective exercise and nonexercise countermeasures, but to what extent these lessons learned will be applicable in the lunar architecture is unknown. Data from this and other studies will provide the basis for the development of an EVA simulator that will not only allow for the verification of prebreathe trials, but will also allow for lunar bed rest studies and longitudinal human system modeling.

## 3.6 Study Limitations

Because this was a continuation of the EWT, one of the first questions to answer was to determine if any differences would be seen between the EWT and IST-1. IST-1 had 3 subjects who had participated in the EWT and 3 new subjects. To look at the test-to-test variability, only the 3 returning subjects were compared. The only 2 carry-over conditions were suited at lunar gravity and 29.6 kPa (4.3 psi) and the unsuited lunar gravity weight-matched (121 kg suit mass) control trial. Figure 47 is this comparison of these test conditions. When comparing the results, the suited metabolic rates from IST-1 were consistently lower than the EWT. The unsuited metabolic rates were not significantly different. Proposed reasons for this variation include increased subject familiarization with partial gravity ambulation, a larger treadmill walking surface and improved weigh-out procedures where each subject's weight on the ground was measured by force plates to within 1.4 kg of the target weight. Previous weigh-out procedures relied only on a load cell measuring POGO off-loading force.



**Figure 47. Lunar locomotion comparison of repeat subjects from both the EWT and IST-1. Suited data refers to the MKIII in the POGO configuration (121 kg suit mass and 29.6 kPa) at lunar gravity. Unsuited data refer to the 121 kg weight-matched condition.**

This study was a continuation of the work started with the EWT and many of the same limitations still exist (1). Those pertinent to this study are described following. Trials in this study were performed on a smooth, firm treadmill surface while a portion of the subject's weight was lifted by a servo-controlled device that limited movement degrees of freedom. Development of simulators that permit more realistic ambulation on planetary surfaces will be required to test a full battery of EVA like tasks and timeline simulations.

The results of this study are based on level ground treadmill ambulation data from 6 male subjects in the MKIII suit. How representative these subjects are of the total astronaut population is not fully quantified, but some representative figures as shown in Appendix C. As these studies progress and eventually when new prototype suits are tested, every effort should be made to include as many subjects as possible as well as to characterize the subject pool's fitness and anthropometry so that an understanding of the factors that contribute to improved performance can be understood.

A significant limitation of the suited gimbal system was the inability to precisely control or accurately set the gimbal center of rotation in relation to the total system CG. Standard procedures were used to configure the systems such that the subject was suspended in a neutral posture while in the suit and then subjects adjusted to their preferred position. All subjects freely chose to align the gimbal center of rotation slightly forward and low position of the system CG. Improved designs of the gimbal system will be required to allow precise and consistent application of CG alignment and to allow systematic variation of CG locations to study the effects of CG on human performance.

Although TGAW was varied in the suited varied weight trials, inertial mass was not varied. All varied weights occurred at a suit mass of 121 kg. Without having the actual mass needed to achieve the correct TGAW in lunar gravity or characterizing the effects of mass independently, the results of the varied weight section have to be viewed as preliminary.

All predictive models need to be viewed as preliminary as the data set is not fully crossed and possible inter-relationships may exist between pressure, gravity and mass that are not yet understood.

Another consideration is that during the reduced-gravity trials the subjects' arms and legs still operated in a 1-g field. Because the weight of the limbs was not reduced, it is possible that the metabolic and biomechanical data may not accurately simulate that which would occur in true reduced gravity environments. One possibility is that the human limbs are generally used in a range of motion (cosine of the angles) where gravity has a reduced effect and therefore most of the energy expended is for force generation and limb velocity. Finally, unsuited data collected in actual lunar gravity during parabolic flight indicate that the walk-run transition speeds during parabolic flight were similar to those found on the POGO (17). These findings suggest that the locomotive patterns used during POGO tests led to the same general walk-run transition speeds and thus may be representative of those that would be used in an actual lunar gravitational environment.

### 3.7 Lessons Learned

Extended familiarization time both suited and unsuited was allowed for all subjects. This may have accounted for some of the differences between the EWT and IST-1 metabolic rates. Every effort should be made in future studies to allowed extended familiarization time and possibly including full familiarization trials to negate a learning effect from start to finish on the dependent variables tested.

The larger treadmill belt width and length was appreciated by the subjects who had experience using the smaller treadmill from the EWT.

Reduced gravity weigh out procedures were improved using the suit/subject/system's static weight on the ground as the target. The force plates in the treadmill were summed to provide this weight, but this process did take longer than subjects would prefer.

Near the end of suited data collection trials, a thermal data collection system was integrated into the suit system cooling loop. Data capability included liquid cooling and ventilation garment (LCVG) flow rate, inlet/outlet temperatures and outlet relative humidity. This system will eventually provide data to understand other ways of calculating metabolic rate as well as to provide inputs and feedback to bioadvisory algorithms, which may play an important role in providing feedback for exploration crewmembers.

As described previously, subject speeds during ambulation were selected on the basis of each individual's PTS. Initially this was done so that walking and running could be compared across different gravities independent of speed. Given that distinctions between walking and running seem to be less clear in reduced gravity, it may be of benefit to switch to fixed speeds for future tests. Also having individual speeds did not allow for direct comparison between conditions and subjects.

For this study, a specific gait was not prescribed, but subjects were directed to maintain a consistent gait throughout the biomechanics data collection period of each trial. While this eliminated most of the problems of gait changing affecting biomechanical data collection, it did complicate data analysis because gait style had a significant impact on many biomechanical metrics. In future tests, subjects may possibly be instructed to employ a symmetric Earth-like gait throughout the study even if an asymmetric gait is favored. Future studies also could examine how changing gait affects results.

The unsuited harness was improved from a comfort standpoint although leg ROM may have still been affected. The kite-surfing harness provided greater surface area in contact with the portion of the subject's body being lifted and the use of neoprene shorts provided another layer of padding.

Having an accurate unsuited 1-g baseline is critical to many analyses including the ESSPI and GCPS. Because this study was an ambulation based study and unsuited earth based ambulation is widely studied and referenced, we did not include a 1-g unsuited condition in this study. We also felt that subjects had enough experience with walking in 1-g such that they would have a valid reference point for GCPS comparisons. While this may not have negatively affected GCPS ratings, this choice caused there to be very limited metabolic and biomechanics data for the subjects in 1-g to look at any objective data comparisons. Population norms may be good reference points, but they are not sufficient for a direct condition to condition comparison for a given subject. All future reduced-gravity planetary surface-based studies are highly encouraged to include an unsuited 1-g condition for every subject.

## **4 CONCLUSIONS**

### **4.1 Contributions of Weight, Mass, Pressure, and Suit Kinematics to Metabolic Cost of MKIII in POGO Configuration**

By varying the suit pressure and system weight, we have been able to identify the portion of metabolic rate specifically related to those components as well as to define the residual cost associated with the combined effects of suit mass, suit kinematics, stability, and suited/unsuited system harness differences for the MKIII suit in its POGO configuration (121 kg [265 lb] including mass of PLSS mockup and gimbal, 29.6 kPa [4.3 psi]) during lunar ambulation.

At the lowest speeds, the weight of the suit/system had no effect on metabolic rate, but as speed increased, the metabolic cost of weight steadily increased reaching 14 percent of the total metabolic cost and accounting for ~35 percent of the metabolic cost of the suit at the three highest speeds. Pressure-volume metabolic work was fairly consistent across the four middle speeds at 15 percent of total metabolic cost and ~38 percent of the metabolic cost of the suit. The remaining suit and system related factors (mass, suit kinematics, stability and harnessing differences) were the most variable component and steadily decreased in absolute and relative terms through the first five speeds from 41 percent to 10 percent of total metabolic cost, but promptly increased at the fastest speed. Full results were shown in Figure 12 and Figure 13

Future tests will drive out the individual contributions of these remaining components as well as examine various inter-relationships and coupling factors present in untested combinations of these variables. By understanding these individual factors, we will be able to provide specific recommendations for suit design requirements, EVA mission planning and overall consumables packaging.



## 4.2 Effects of Varied Weight, Mass and Pressure on Suited Human Performance

Initial findings suggest that for level ground ambulation, suit pressure has a minimal influence on metabolic rate, biomechanics, or on subjective assessments of exertion and operator compensation for the group as a whole. However, some evidence, based on different metabolic profiles between subjects (Figure 15), indicates that pressure may be important within individual subjects for level ground ambulation.

The observation that metabolic rate was essentially unchanged by suit pressure is supported by the suit elements description of the MKIII suit as constant volume. Different suit designs with different joint designs and sequencing might be affected differently by suit pressure, especially if constant volume joints were changed to soft joints. These observations are limited to ambulation and do not imply that suit pressure would not have a significant effect on crewmembers performing upper body and hand intensive exploration tasks.

Initial findings show no consistent trend between added mass variations of 0 to 34 kg and metabolic rate in the unsuited condition. However, it was possible that this is a result of hardware limitations. Modifications to the spider gimbal system to accommodate shirt-sleeved subjects should provide a better platform to investigate the effects of mass in future tests.

Gravity level does have a large effect on performance. At this point, we hypothesize that much of the change in performance is because of the difference in TGAW. At the two slowest speeds this change in weight did not affect average metabolic rate. At the faster speeds, the differences became significant, reaching up to  $\sim 15 \text{ mL} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$  at the fastest speeds between gravity levels of 0.12-g and 0.32-g. Based on an analysis of oxygen transport costs, which can be thought of as a human's equivalent of gas mileage, we suggest that a suit mass of 186 kg or less may be necessary for an efficient performance in a 10 km walkback contingency; the most efficient walkback speed for a 186 kg suit might be  $1.4$  to  $2.1 \text{ m} \cdot \text{s}^{-1}$ , and the most efficient walkback speed for a 63 to 121 kg suit might be  $1.8$ - $2.6 \text{ m} \cdot \text{s}^{-1}$ , although many factors may affect this selection including cooling limitations (1), terrain (10) as well as an understanding of how similar a change in TGAW from just an alteration in weight represents a true change in suit mass.

The metabolic cost of the suit unrelated to weight was tied to speed. At the slower walking speeds, there was little to no increase as gravity increased, but with the faster walking speeds and running speeds clearly showing an increase as gravity level increased. This indicates that interactions between weight and speed exist that were not fully understood and are not consistent across the whole range of ambulation speeds.

Perceived exertion increased as gravity increased and the increase in exertion with speed was greater at higher gravity levels. For all subjects at all speeds, gravity levels  $\leq 0.22$ -g had GCPS ratings  $\leq 5$ , with most in the acceptable range of  $\leq 4$ . In many cases, the heavier weights were also acceptable, but there were several ratings  $\geq 6$ , especially at higher speeds.

Biomechanical data showed an increase in stance time, cadence, and peak vertical ground-reaction force with an increase in weight and speed, as would be expected. These changes with increases in both speed and weight demonstrate that the amount of work done by the subject is also increasing. Biomechanical data also showed little difference with changes in pressure. This is also to be

expected for a near constant volume suit with pressure regulation. Without a dramatic buildup of internal pressure, there should be no mechanical changes in the suit that would affect performance. Interpretation of joint ROM data was limited because of anomalous findings. These anomalies were found at a specific gravity and pressure, suggesting a complex and unexpected relation with the system at those conditions.

#### 4.3 Comparison of Locomotion in the MKIII at POGO Configuration to MKIII with the Waist Bearing Locked

Metabolic data indicates that locking the MKIII waist bearing did not affect metabolic rate during level ground ambulation. However, subjective ratings did differ between conditions, with the average RPE slightly higher and GCPS ratings approximately 1 to 2 levels higher in the waist-locked condition than in nominal operations. Interpretation of biomechanical differences was limited to the high variability of gait selection within and between subjects.

#### 4.4 Predictive Models of Metabolic Rates, Subjective Assessments and Suit Kinematics

A preliminary multiple linear regression model was developed to predict the metabolic cost of locomotion in the MKIII suit as a function of the properties of the suit, the anthropometry of the subject and the speed of locomotion. While preliminary and descriptive in nature, this model highlights the possible applications for a complete model including: refining operational concepts, defining suit requirements and predicting consumable usage. Separate models to predict RPE and to predict the probability of a given GCPS rating were also developed. Models to determine joint cycles and other lifecycle aspects of the suit are in progress. Eventually, with the inclusion of additional data and improved understanding of various inter-relationships, these models will be combined into an all inclusive predictive algorithm, which would provide one comprehensive user friendly tool that would incorporate the results of applicable human performance testing in reduced gravity.

#### 4.5 Secondary Objectives

This test series provides an ideal opportunity to use the data collected for much more than to address the specific primary objectives. Lessons learned from this test can be used to better testing technology and lunar analog environments as well as prepare for future testing and requirements verification of EVA suit candidates. Data will be used to develop an EVA simulator for use on prebreathe protocol verification and exercise countermeasure studies. Metrics to compare suited to unsuited performance in both reduced and earth gravity help provide a reference point to determine what ideal suited human performance entails. One of the key applications of this study was to further the knowledge of suited human performance. While this has direct application to certain questions that are currently being looked at, it will undoubtedly help direct the questions of the future as well.

#### 4.6 Summary

IST-1 addressed the primary objectives of the study and has begun to provide some of the data to answer secondary objectives. As more studies are completed, these predictive models, suit parameter inter-relationships, standard measures and new metrics such as ESSPI will become complete products allowing for evidence-based recommendations to optimize suit design and plan EVA operational constraints and consumable targets.

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## **Appendix A: Sub-maximal Test Termination Criteria**

### Test Termination Criteria for All Submaximal Testing

1. Subject request to stop at any time
2. Subject's heart rate or measured  $\text{VO}_2$  at level  $>85\%$   $\text{VO}_{2\text{pk}}$  for 2 min or more
3. Failure of POGO hardware and/or treadmill system

### ADDITIONAL Test Termination Criteria for Suited Submaximal Testing

1. Expired  $\text{CO}_2$  levels greater than 5%
2. If subject reports discomfort rating  $\geq 7$  (on 10-point scale) for two consecutive recording periods, subject will be asked to terminate the test. If subject asks to continue, they will be allowed to continue until they meet condition 3
3. Discomfort rating  $\geq 7$  for 3 recording periods (may be non-consecutive) or severe pressure point
4. Engineering hardware failure such as in suit or suit environmental control (These standard/approved engineering termination criteria were described in the detailed test plan (CTSD\_AHI\_0009) and addressed in the test readiness review.

## Appendix B: Ratings Scales for Subjective Measures

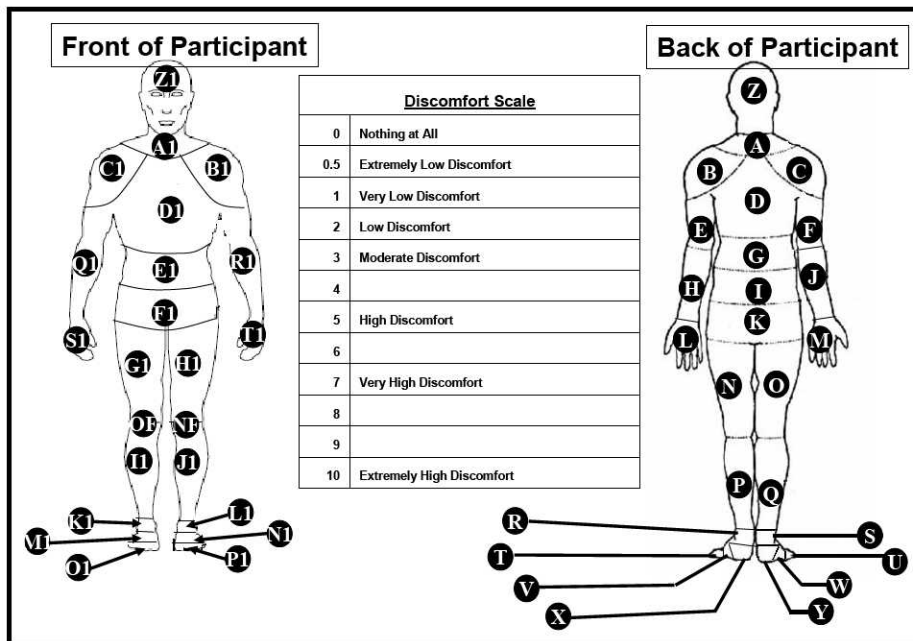
### Gravity Compensation and Performance Scale

1	<b>Excellent</b> – easier than 1-g
2	<b>Good</b> – equivalent to 1-g
3	<b>Fair</b> – minimal compensation for desired performance
4	<b>Minor</b> – moderate compensation for desired performance
5	<b>Moderately objectionable</b> – considerable compensation for adequate performance
6	<b>Very objectionable</b> – extensive compensation for adequate performance
7	<b>Major deficiencies</b> – considerable compensation for control, performance compromised
8	<b>Major deficiencies</b> – intense compensation, performance compromised
9	<b>Major deficiencies</b> – adequate performance not attainable with maximum tolerable compensation
10	<b>Major deficiencies</b> – unable to perform task

### Borg Rating of Perceived Exertion Scale (RPE)

6	No exertion at all
7	Extremely light
8	
9	Very light
10	
11	Light
12	
13	Somewhat hard
14	
15	Hard (heavy)
16	
17	Very hard
18	
19	Extremely hard
20	Maximal exertion

## Corlett & Bishop Discomfort Scale



## Bedford Thermal Scale

-3	Much Too Cool
-2	Too Cool
-1	Comfortably Cool
0	Comfortable
1	Comfortably Warm
2	Too Warm
3	Much Too Warm

## Thermal Preference

-2	Much warmer
-1	A Bit Warmer
0	No Change
1	A Bit Cooler
2	Much Cooler

## Appendix C: Subject Comparison to General Astronaut Population

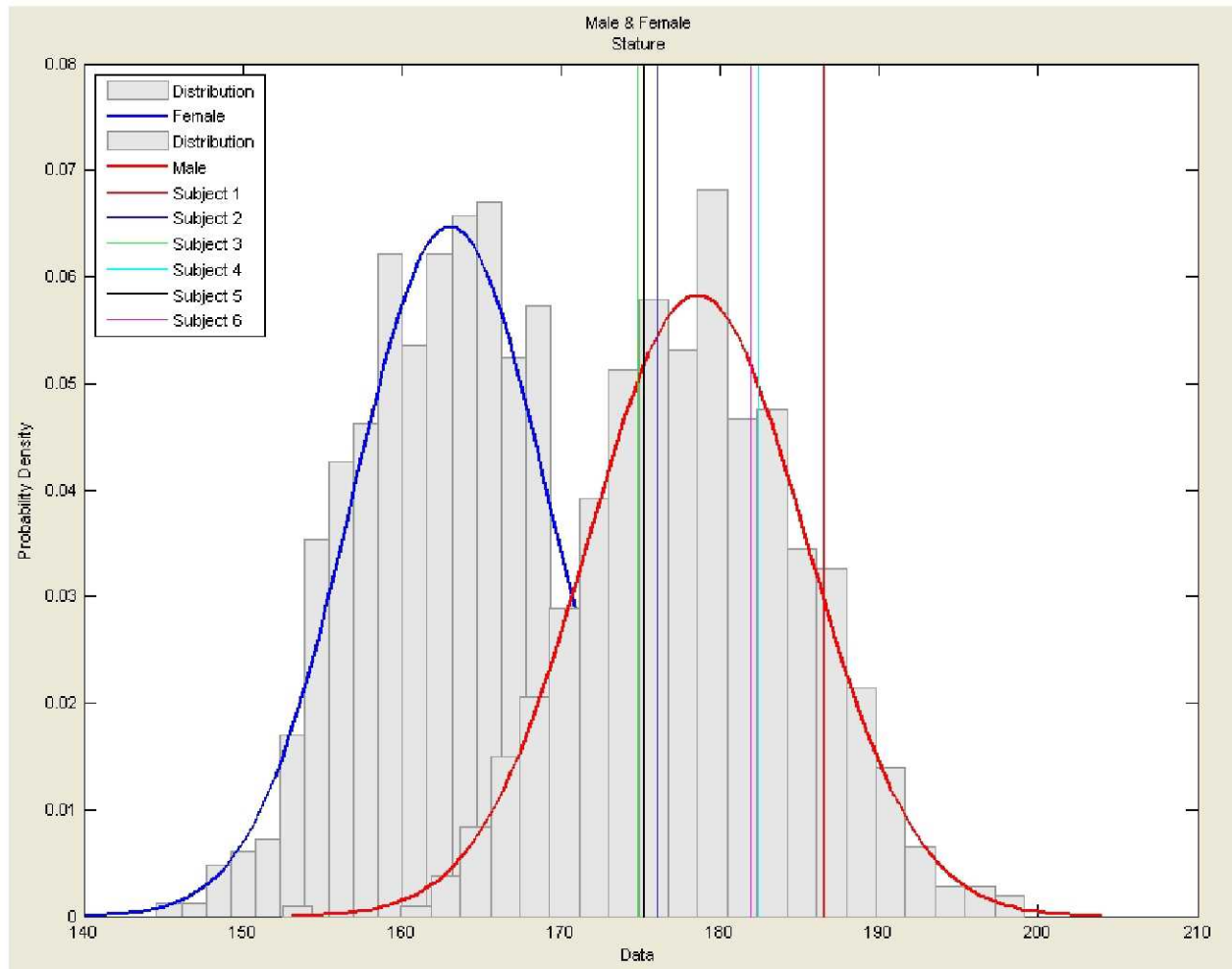
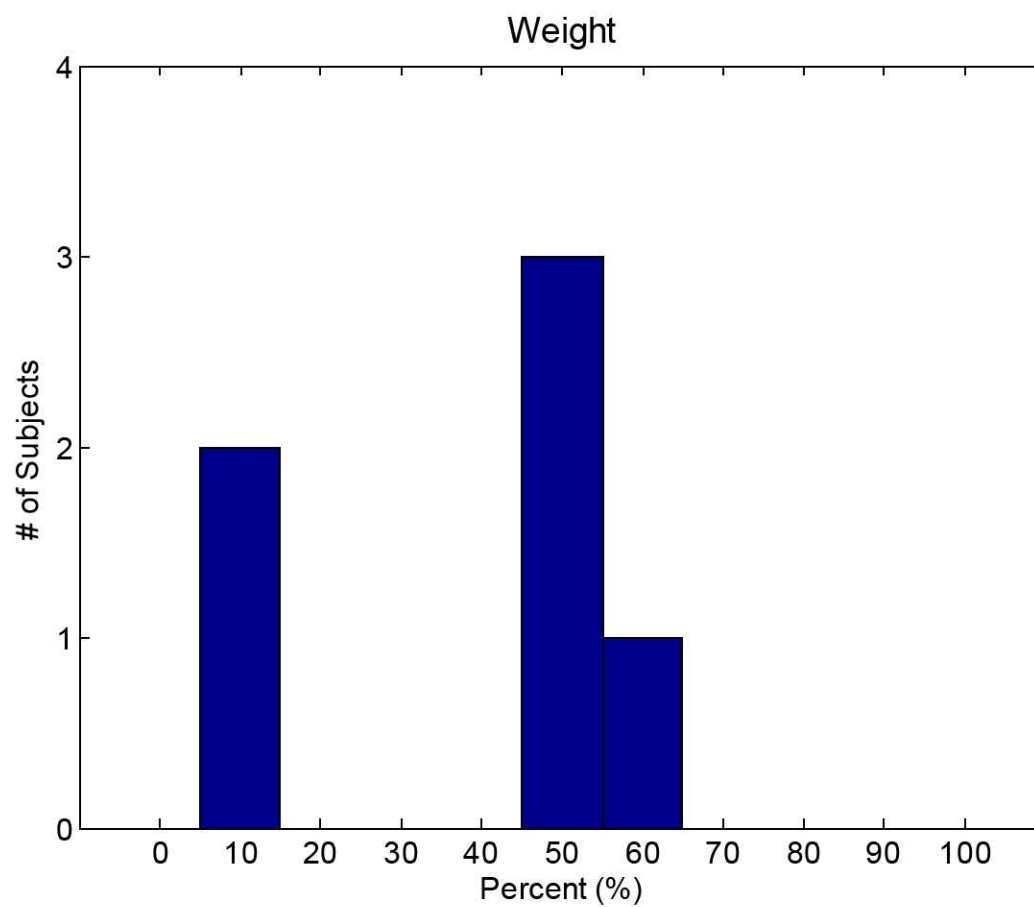


Figure 48. Distribution of IST-1 subject height in relation to the astronaut population





**Figure 49. Distribution of IST-1 subject body mass in relation to the astronaut population**

## **Appendix D: Initial IST-1 Quick-Look Report**

### **EVA Systems Project FY'07 SE&I Test 1 Quick Look Test Report**

To: EVA Systems Project Test and Facilities, Manager / Jeff Patrick  
EPSP Manager/Mike Gernhardt  
EPSP Test Lead/Jason Norcross  
From: EVA Systems Project Test and Facilities, Test Lead / Jessica Vos  
ESCG EVA Test Team / Kevin Rullman  
Date: August 7, 2007  
Subject: EVA System Project FY'07 SE&I Test 1 Quick Look Report

#### ***Objectives:***

Phase I: Measure the transport costs of inertial mass (shirt-sleeve only) during lunar ambulations.

- Add mass to the subjects while controlling the Pogo system to maintain a constant weight

Phase II: Measure the effects of varied suit pressure during lunar ambulations.

- Constant mass and weight (or Pogo offloading)
- 1.0, 3.0, 4.3, 5.0, and 6.5 psi

Phase III: Measure the effects of varied suit weight (or POGO offloading) during lunar ambulations.

- Constant mass and pressure
- 0.12, 0.17, 0.22, 0.27, and 0.32G equivalent offloading

Dates Performed: March 20 – July 24, 2007

This memo serves to document the testing accomplishments for the EVA Systems Project FY'07 SE&I Test 1 conducted during the period from March 20 – July 24, 2007. This report does not provide formal Constellation EVA Systems Project or EVA Physiology, Systems, and Performance Project (EPSP) recommendations or conclusions. A complete technical report documenting the EVA Systems Project and EPSP recommendations stemming from this test will be forthcoming following review of test data. The test team observations provided in this report should be taken as initial indicators of results only, and are not to be used for EVA System or EPSP Project recommendations.

#### ***General Summary***

The EVA Systems Project FY'07 SE&I Test 1 was performed at the Space Vehicle Mockup Facility (SVMF) at JSC. This was an integrated test jointly performed by the Constellation EVA Systems Project and the Human Research Program's EPSP. The purpose of this test was to collect human performance data (metabolic, human kinematics, thermal, subjective comfort, etc), given variations in suited operating pressure and suited weight for lunar ambulation tasks. CPHS approval for this test activity was obtained on February 22, 2007. Two test readiness reviews, one chaired by Craig

Dinsmore from the Space Suit Systems Branch (EC5), and the other chaired by Arne Aamodt from SVMF (DX14), were held before the start of this test series.

Three separate “engineering runs” were successfully conducted with subjects from the JSC engineering directorate to verify the data collection methods for each of the three phases of testing listed above. A total of six primary test subjects (selected from the current NASA Astronaut Corps) completed each phase of the test, which consisted of two suited test days and one unsuited (shirt-sleeve) test day. The three different test days (or phases) were not required to be performed in any particular order. Test subject schedules, suit availability, and test area configuration mostly dictated the day-to-day testing order. An average test day, shirt-sleeve or suited, consisted of ~4.5 hours of testing. All testing was completed with only a few hardware anomalies and/or test related delays, which are detailed in the section entitled “Hardware Anomalies and Test Related Delays.”

### ***Test Equipment***

#### **POGO, MK III Suit, and Shirt-Sleeve Harness**

The three phases of this test used the Partial Gravity Simulator (a.k.a. “POGO”) as the primary weight relief system for the test subjects in both the shirt-sleeve and the suited configurations. The pneumatic piston of the Pogo was attached to the Mark III Advanced Space Suit Technology Demonstrator (MKIII) Suit via the Spider Gimbal System, which allowed for limited rotational movement by the suited subject in the roll, pitch, and yaw axes while attaching to the volumetric PLSS mockup located on the hatch of the MK III HUT. The Pogo weight relief was varied during this test to emulate varied EVA System weights (referred to in this report as difference in gravity levels). For the shirt-sleeve configuration (with the weighted X-Vest), the POGO piston attached to a spreader bar that distributed the offloading force to the body restraint harness via 4 straps (2 on each side). The suited tests required the use of certified breathing air, for which the SVMF brought a tube trailer online soon after the test series began to alleviate the large number of K-bottles required for each test. The tube trailer greatly reduced the logistical management of the breathing air supply for JSC, which became an issue after the Walkback Test in June of 2006 and threatened the schedule for this test series as well.

#### **Treadmill and Force Plates**

The subjects ambulated on the newly acquired VacuMed Research Treadmill (Model #13610) which provided a much larger surface area for translating and functioned as intended throughout the test. As a custom design modification, four AMTI force platforms (Model #OR6-5-2000) were installed by the vendor before delivery of the treadmill to accommodate our data collection needs. Ground Reaction Force data was captured at 1000 Hz. For more information regarding the COTS treadmill design, please refer to this website:

<http://www.vacumed.com/zcom/product/Product.do?compid=27&prodid=688>.

#### **Communications**

Both wireless and hardwired communication systems were utilized at various stages in the test. The wireless system used at the beginning of the test was on loan from the CTSD Systems Test Branch (EC4) and had to be returned mid-test, at which point it was replaced with the hardwire system (owned by EC5). Although the hardwire system proved to be sufficient, the wireless system was preferred over the hardwired system because of the mobility requirements of many of the critical test

personnel inside the test area and the improved safety aspects because of reductions in wires spanning the test floor area.

### **Motion Capture System**

A Vicon MX40+ system, with 12 cameras total, captured video at 100Hz using Near-IR strobes (essentially the same wavelength as the older system used in the Walkback test in June 2006) and 4-megapixel sensors. Vicon Nexus software was used for motion capture and reconstruction of motion and ground reaction force data.

### **Metabolic Rate and Heat Load Data Collection**

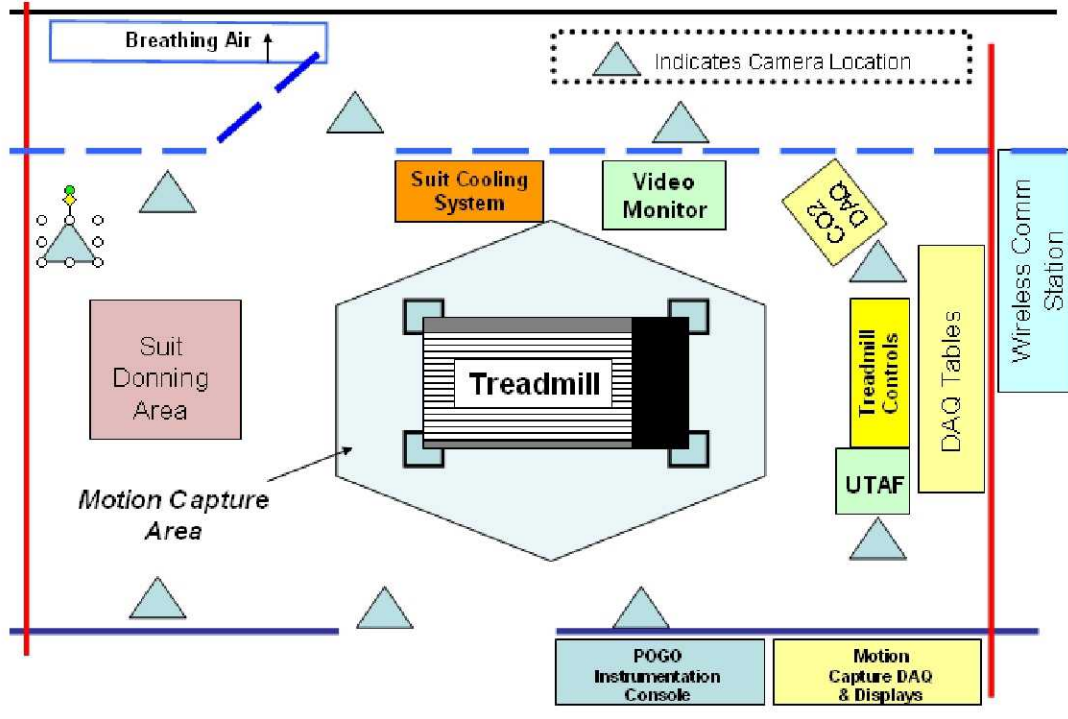
For the shirt-sleeve tests, each subject's met rate was determined from the continuous measurement of  $\text{VO}_2$ , carbon dioxide ( $\text{CO}_2$ ) production, and expiratory volume ( $V_E$ ) using a headset/mouthpiece connected to a True One 2400 metabolic cart from Parvo Medics. During exercise in the MKIII suit, metabolic rate was calculated using the following variables: measured suit ventilation rate; expired  $\text{CO}_2$  concentration in the exhaust umbilical (captured via a CD-3A Infrared Carbon Dioxide Analyzer from AEI Technologies); and the regression between  $\text{VCO}_2$  and  $\text{VO}_2$  as measured during each subject's  $\text{VO}_2$  peak test. This technique and hardware were identical to those currently used during suited NBL test and training activities.

Heart rate was measured from a Polar Heart Rate Monitor for both shirt-sleeve and suited test configurations.

Cooling water temperatures were measured at the inlet and outlet of the Liquid Cooling Garment (LCG) as well as at the outlet of the cooling cart (which had been newly remodeled to handle a greater heat load after the Walkback Test) during the suited test activities. This temperature data provided an indication of the heat load being produced by the each subject (and removed by the LSC) for each suited test.



## Test Area Layout Diagram (POGO Area of SVMF, B9 High Bay)



## Test runs completed per date are as follows:

22-Mar				
Varied Pressure				
Start Time	Speed	Suit Pressure	Gravity Level	Conditions/Notes
11:18:00	1.7 to 5.7 mph	3.0 psi	1/6-g	Suited
11:45:30	1.7 to 5.7 mph	5.0 psi	1/6-g	Suited
12:22:00	1.7 to 5.7 mph	6.5 psi	1/6-g	Suited

27-Mar				
Varied Pressure				
Start Time	Speed	Suit Pressure	Gravity Level	Conditions/Notes
9:45:30	1.9 to 5.9 mph	0 psi	1/6-g	Suited - no helmet
10:44:00	1.9 to 5.9 mph	3.0 psi	1/6-g	Suited
11:15:38	1.9 to 5.9 mph	5.0 psi	1/6-g	Suited
11:48:20	1.9 to 5.9 mph	6.5 psi	1/6-g	Suited

4-Apr				
Varied Weight				
Start Time	Speed	Suit Pressure	Gravity Level	Conditions/Notes
9:24:24	1.7 to 5.7 mph	4.3 psi	0.12-g	Suited
9:59:00	1.7 to 4.7 mph	4.3 psi	0.32-g	Suited
11:14:18	1.7 to 4.7 mph	4.3 psi	0.27-g	Suited
11:42:22	1.7 to 5.7 mph	4.3 psi	1/6-g	Suited
12:13:27	1.7 to 4.7 mph	4.3 psi	0.22-g	Suited
12:38:30	1.7 to 5.7 mph	1.0 psi	1/6-g	Suited
1:02:27	1.7 to 5.7 mph	4.3 psi	1/6-g	Suited - waist locked

11-Apr				
Varied Pressure				
Start Time	Speed	Suit Pressure	Gravity Level	Conditions/Notes
10:11:52	2.0 to 6.0 mph	5.0 psi	1/6-g	Suited
10:44:48	2.0 to 6.0 mph	4.3 psi	1/6-g	Suited
11:11:10	2.0 to 6.0 mph	3.0 psi	1/6-g	Suited
11:37:25	2.0 to 6.0 mph	1.0 psi	1/6-g	Suited
DNF	DNF	DNF	DNF	suit malfunction – see section below for details

12-Apr				
Varied Pressure				
Start Time	Speed	Suit Pressure	Gravity Level	Conditions/Notes
2:07:08	1.5 to 5.5 mph	1.0 psi	1/6-g	Suited
2:30:40	1.5 to 5.5 mph	3.0 psi	1/6-g	Suited
2:54:35	1.5 to 5.5 mph	6.5 psi	1/6-g	Suited
3:21:45	1.5 to 5.5 mph	4.3 psi	1/6-g	Suited
3:47:02	1.5 to 5.5 mph	5.0 psi	1/6-g	Suited

17-Apr				
Varied Weight				
Start Time	Speed	Suit Pressure	Gravity Level	Conditions/Notes
9:21:00	1.5 to 5.5 mph	4.3 psi	0.12-g	Suited
9:48:30	1.5 to 4.5 mph	4.3 psi	0.27-g	Suited
10:26:45	1.5 to 4.5 mph	4.3 psi	0.22-g	Suited
10:56:30	1.5 to 4.5 mph	4.3 psi	0.32-g	Suited
11:23:30	1.5 to 5.5 mph	4.3 psi	1/6-g	Suited - waist locked

18-Apr				
Varied Weight				
Start Time	Speed	Suit Pressure	Gravity Level	Conditions/Notes
9:16:24	1.9 to 4.9 mph	4.3 psi	0.32-g	Suited
9:54:10	1.9 to 4.9 mph	4.3 psi	0.22-g	Suited
10:31:25	1.9 to 5.9 mph	1.0 psi	1/6-g	Suited
10:59:15	1.9 to 5.9 mph	4.3 psi	0.12-g	Suited
11:30:34	1.9 to 4.9 mph	4.3 psi	0.27-g	Suited
12:01:18	1.9 to 5.9 mph	4.3 psi	1/6-g	Suited
12:27:15	1.9 to 5.9 mph	4.3 psi	1/6-g	Suited - did not complete final speed

19-Apr				
Varied Weight				
Start Time	Speed	Suit Pressure	Gravity Level	Conditions/Notes
13:15:05	2.0 to 5.0 mph	4.3 psi	0.22-g	Suited
13:53:45	2.0 to 5.0 mph	4.3 psi	0.32-g	Suited
14:49:10	2.0 to 6.0 mph	4.3 psi	0.12-g	Suited
15:30:07	2.0 to 5.0 mph	4.3 psi	0.27-g	Suited
16:01:02	2.0 to 6.0 mph	6.5 psi	1/6-g	Suited

26-Apr				
Varied Pressure				
Start Time	Speed	Suit Pressure	Gravity Level	Conditions/Notes
9:55:47	1.4 to 5.4 mph	6.5 psi	1/6-g	Suited
10:24:30	1.4 to 5.4 mph	5.0 psi	1/6-g	Suited
11:08:21	1.4 to 5.4 mph	3.0 psi	1/6-g	Suited
11:33:50	1.4 to 5.4 mph	1.0 psi	1/6-g	Suited

27-Apr				
Varied Weight				
Start Time	Speed	Suit Pressure	Gravity Level	Conditions/Notes
8:53:00	1.4 to 5.4 mph	4.3 psi	1/6-g	Suited
9:46:20	1.4 to 4.4 mph	4.3 psi	0.32-g	Suited
10:30:45	1.4 to 4.4 mph	4.3 psi	0.27-g	Suited
10:54:30	1.4 to 4.4 mph	4.3 psi	0.22-g	Suited
11:31:00	1.4 to 5.4 mph	4.3 psi	0.12-g	Suited
12:19:00	1.4 to 5.4 mph	4.3 psi	1/6-g	Suited

8-May				
Varied Mass				
Start Time	Speed	Gravity Level	Added Mass	Conditions/Notes
9:42:45	1.7 to 5.7 mph	1/6-g Weighted		Shirt-Sleeve
10:14:11	1.7 to 4.7 mph	0.27-g Weighted		Shirt-Sleeve
10:58:44	1.7 to 5.7 mph	1/6-g Weighted	25 lb	Shirt-Sleeve
11:34:45	1.7 to 5.7 mph	1/6-g Weighted	50 lb	Shirt-Sleeve
12:07:15	1.7 to 5.7 mph	1/6-g Weighted	75 lb	Shirt-Sleeve

9-May				
Varied Mass				
Start Time	Speed	Gravity Level	Added Mass	Conditions/Notes
9:19:52	2.0 to 6.0 mph	1/6-g Weighted	75 lb	Shirt-Sleeve
9:55:51	2.0 to 6.0 mph	1/6-g Weighted	50 lb	Shirt-Sleeve
10:28:19	2.0 to 5.0 mph	0.27-g Weighted		Shirt-Sleeve
11:01:14	2.0 to 6.0 mph	1/6-g Weighted		Shirt-Sleeve
11:40:37	2.0 to 6.0 mph	1/6-g Weighted	25 lb	Shirt-Sleeve
12:14:45	2.0 to 5.0 mph	0.32-g Weighted		Shirt-Sleeve

10-May				
Varied Mass				
Start Time	Speed	Gravity Level	Added Mass	Conditions/Notes
14:41:00	1.5 to 5.5 mph	1/6-g Weighted	50 lb	Shirt-Sleeve
15:21:50	1.5 to 5.5 mph	1/6-g Weighted	25 lb	Shirt-Sleeve
16:10:41	1.5 to 5.5 mph	1/6-g Weighted	75 lb	Shirt-Sleeve
16:46:55	1.5 to 4.5 mph	0.27-g Weighted		Shirt-Sleeve
17:24:24	1.5 to 5.5 mph	1/6-g Weighted		Shirt-Sleeve

15-May				
Varied Mass				
Start Time	Speed	Gravity Level	Added Mass	Conditions/Notes
9:13:00	1.9 to 5.9 mph	1/6-g Weighted	25 lb	Shirt-Sleeve
9:54:49	1.9 to 5.9 mph	1/6-g Weighted		Shirt-Sleeve
10:32:31	1.9 to 5.9 mph	1/6-g Weighted	50 lb	Shirt-Sleeve
11:06:20	1.9 to 5.9 mph	1/6-g Weighted	75 lb	Shirt-Sleeve
11:43:32	1.9 to 4.9 mph	0.27-g Weighted		Shirt-Sleeve



17-May				
Varied Mass				
Start Time	Speed	Gravity Level	Added Mass	Conditions/Notes
8:59:41	1.4 to 4.4 mph	0.27-g Weighted		Shirt-Sleeve
9:34:50	1.4 to 5.4 mph	1/6-g Weighted	75 lb	Shirt-Sleeve
10:21:18	1.4 to 5.4 mph	1/6-g Weighted		Shirt-Sleeve
11:00:31	1.4 to 5.4 mph	1/6-g Weighted	25 lb	Shirt-Sleeve
11:31:32	1.4 to 4.4 mph	0.32-g Weighted		Shirt-Sleeve
12:07:10	1.4 to 5.4 mph	1/6-g Weighted	50 lb	Shirt-Sleeve

23-May				
Varied Pressure				
Start Time	Speed	Suit Pressure	Gravity Level	Conditions/Notes
14:07:30	2.2 to 6.2 mph	3.0 psi	1/6-g	Suited
14:32:38	2.2 to 6.2 mph	5.0 psi	1/6-g	Suited
14:58:42	2.2 to 6.2 mph	1.0 psi	1/6-g	Suited
15:30:46	2.2 to 6.2 mph	6.5 psi	1/6-g	Suited

25-May				
Varied Weight				
Start Time	Speed	Suit Pressure	Gravity Level	Conditions/Notes
13:19:39	2.2 to 5.2 mph	4.3 psi	0.32-g	Suited
13:51:27	2.2 to 5.2 mph	4.3 psi	0.22-g	Suited
14:24:21	2.2 to 6.2 mph	4.3 psi	0.12-g	Suited
15:01:24	2.2 to 6.2 mph	4.3 psi	1/6-g	Suited
15:25:02	2.2 to 5.2 mph	4.3 psi	0.27-g	Suited
15:48:13	2.2 to 6.2 mph	4.3 psi	1/6-g	Suited - waist locked

24-Jul				
Varied Mass				
Time	Speed (mph)	Gravity	Added Mass	Conditions/Notes
13:12:30	2.2 to 6.2 mph	1/6-g Weighted		Shirt-Sleeve
13:48:48	2.2 to 5.2 mph	0.27-g Weighted		Shirt-Sleeve
14:19:51	2.2 to 5.2 mph	0.32-g Weighted		Shirt-Sleeve
14:59:51	2.2 to 6.2 mph	1/6-g Weighted	75 lb	Shirt-Sleeve
15:34:01	2.2 to 6.2 mph	1/6-g Weighted	50 lb	Shirt-Sleeve
16:09:43	2.2 to 6.2 mph	1/6-g Weighted	25 lb	Shirt-Sleeve

### *Hardware Anomalies and Test-Related Delays*

1. On 4/09/07, the treadmill vendor was called in to make some minor adjustments to the internal force platform mounting structure inside the treadmill deck, as one of the force plates had come loose and, therefore, was producing corrupt ground reaction force data. The adjustment improved the quality of data received from each of the four AMTI force platforms for the remainder of the test.
2. One scheduled run had to be canceled the day of the test before starting because of data collection problems with the Vicon motion capture system, which is maintained and operated by the Anthropometrics and Biomechanics Facility (ABF). The system manufacturer (located on the west coast) had to be contacted, shortly after which the problem was resolved and the system was back in operation in time for the test the next day. There were no other problems or test delays with this system for the remainder of the test.
3. One test subject was replaced with another crewmember test subject early in the test (after his first suited run) because of a sub-optimal Mark III suit fit and general comfort. Until more suit sizing elements are procured (specifically boots, HUT, and HLT assemblies), the current suit size will continue to be a major driver in subject selection for tests involving the MK III suit.
4. The suited run on April 11 had to be discontinued before the conclusion of the planned test activities because of a structural problem discovered on the MK III suit. A crack was found on one of the four bosses (attachment points for the PLSS mockup and the Spider Gimbal System) located on the lower left corner of the composite hatch. Upon the finding, the test team immediately stopped the test and the subject egressed the suit. The hatch was removed from the suit and taken to the Non-Destructive Evaluations Lab in the Materials and Processes Branch (ES4) onsite at JSC for further inspection. X-ray analysis found evidence of cracking and dense foreign matter/inclusions in the composite material in all four bosses. For more information regarding this analysis, contact Kenneth Hodges (ES4). After the in-house analysis had been performed, the hatch was sent back to Airlock (the manufacturer) for repair. Meanwhile, the older, heavier cast aluminum hatch was placed on the suit for the remainder of the test activity.
5. The waist bearing and the upper-thigh bearings on the suit began to show evidence of accelerated wear-and-tear because of the number of cycles placed on them during this test series. Energy dispersive spectroscopy (EDS) analysis performed by ES4 of the blackish-colored debris found inside the waist bearing after only about 20 hours of testing (which is half the time required for a full maintenance cycle on the suit hardware per CTSD-ADV-197 and/or JSC 33497) showed that the black debris was mostly oxidized aluminum mixed with some Braycote (common lubricating material), the presence of which meant that the waist bearing was wearing down at an accelerated rate as used in this test. As a result, the suit techs had to perform a more detailed maintenance procedure than usually required between tests (within the normal 40-hour maintenance cycle). This finding also resulted in a change to the test plan, which originally called for testing at 0.0 psid, as that specific test point proved to be

too hard on the suit bearings. The test point was changed to be conducted “vent pressure”, or 1.0 psid, to protect the functionality of the suit and the bearings.

6. Some minor test delays were caused by the fact that the reflective markers used as part of the motion capture data collection system did not stay on the suit very well at the lower pressures, which caused the team to have to pause the test activity several times to replace the critical markers at the lower pressures.
7. Upon set up of the entire test area, the test team learned (by trial and error) that the power supply provided by the SVMF is not “clean” and, therefore requires power conditioners to provide reduced noise in the power supplied to the test and data collection equipment, which results in more clean and accurate test data.
8. Because of the large number of planned test days (21 total), and the number of MK III suit fit checks required for this test activity (4 total, scattered throughout the test), the test scheduling was susceptible to and compounded by facility availability, crew availability, the suit maintenance requirements, and the suit availability (as it was being used in other tests and fit-check activities during the same time frame). In general, aligning all three of these factors and accomplishing 21 days of testing within the original test schedule proved to be a challenging task. As a result the test schedule was often changed and/or delayed.

### ***Overall Test Summary***

All the test objectives planned for this test were completed without incident. Excellent participation and cooperation was exhibited by all parties involved through all aspects of test planning and test execution. The recommendations and conclusions from this test will be documented in the final technical report following video review and debriefs with the SE&I teams from the EVA System and EPSP projects.